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GEOACOUSTIC MODELS OF THE SEA FLOOR: GULF OF OMAN, ARABIAN SEA, AND SOMALI BASIN (U)

Edwin L. Hamilton and Richard T. Bachman

15 June 1979

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(C) The objectives of this investigation were as follows:

- To determine and study those characteristics of the sea floor that affect the propagation of sound and the predictions of low-frequency surveillance-system performance;
- To support specific underwater acoustic experiments in the northwestern Indian Ocean during the BEARING STAKE exercise by furnishing information on acoustic and related properties of sediment and rock layers in the form of geoacoustic models of the sea floor; and

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20. Abstract. (Continued)

- To produce additional geoacoustic models of the sea floor to allow extrapolation of the results of the bottom-loss experiments into adjacent areas.

SUMMARY (U)

OBJECTIVES (U)

(C) The objectives of this investigation were as follows:

- To determine and study those characteristics of the sea floor that affect the propagation of sound and the prediction of low-frequency surveillance-system performance.
- To support specific underwater acoustic experiments in the northwestern Indian Ocean during the BEARING STAKE exercise by furnishing information on acoustic and related properties of sediment and rock layers in the form of geoacoustic models of the sea floor.
- To produce additional geoacoustic models of the sea floor to allow extrapolation of the results of the bottom-loss experiments into adjacent areas.

RESULTS (U)

1. (U) To formulate a geoacoustic model of the sea floor to support theoretical studies of underwater acoustics, experiments at sea, and predictions of surveillance-system performance, the following information is required for most current work in underwater sound propagation: thicknesses of layers, compressional wave (sound) velocity in each layer, sound velocity gradient through the layers, sound attenuation in each layer, and density in each layer.

(U) Newer and more sophisticated mathematical-computer models involving sound interaction with the sea floor also require the gradient of sound attenuation through the layers, the density gradient through the layers, the shear wave velocity and attenuation, and those gradients which can be used with density and compressional wave velocity to derive other elastic properties. (All of the above information is provided in 19 geoacoustic models in the appendices to this report.)

2. (C) Part II of this report is concerned with ten geoacoustic models of the sea floor for three areas in the northwest Indian Ocean in which bottom-loss measurements were made during the BEARING STAKE expedition (January to April 1977). The three areas are in the Gulf of Oman (area 1B), the Arabian Sea (area 3), and the Somali Basin (area 4) off northeast Africa. Most of the necessary environmental data were collected from the USNS WILKES (T-AGS-33). Additional bathymetric data were taken by USNS KINGSPORT (T-AG-164) and USNS MIZAR (T-AGOR-11) The environmental data concerning the sea floor were furnished the writers by NAVOCEANO (Codes 3408 and 3432) and NORDA (Code 341). These data, plus information from the scientific literature, were used to formulate the models. The actual models in the form of tables with footnotes are in Appendix A. The methods used to derive the values listed in the tables and discussions of supporting data (water-mass information, bathymetric charts and ship's tracks, and profiles of the sea floor) are described in this report.

3. (C) Part III presents nine additional geoacoustic models which can be used to extrapolate geophysical and geologic data within adjacent geomorphic provinces. The three general areas discussed in Part III are distinctive geomorphic provinces: the Oman Basin,

Arabian Fan and adjacent areas in the Arabian Basin, and Somali Basin. It is concluded that experimental bottom-loss data can be widely extrapolated within these provinces.

RECOMMENDATIONS (U)

(U) The production of geoacoustic models of the sea floor to support low-frequency surveillance-system experiments and to predict performance requires detailed, quantitative knowledge of all items previously discussed. All data should be collected at sea, where important experiments are performed. However, the state of the art does not presently permit routine data collection at sea for several of the items, which must be predicted in a generalized manner (based on measurements in similar types of sediments and rocks elsewhere).

(U) Of those items listed, it is especially recommended that the Navy strongly support basic and applied research in the areas of (1) compressional wave (sound) velocities at the sediment surface and velocity profiles and gradients in the sea floor, (2) attenuation of compressional waves as a function of depth in the sea floor at surveillance frequencies, and (3) shear wave velocity, attenuation, and gradients of these properties in the sea floor.

(U) CONTENTS (U)

(U) CONTENTS (Continued) (U)

PART I. INTRODUCTION (U)

BACKGROUND (U)

(C) This report is concerned with geoacoustic models of the sea floor in three general areas of the northwest Indian Ocean (figure 1) in which measurements were made of energy losses (bottom losses) when sound interacted with the sea floor during the BEARING STAKE expedition (January to April 1977). Part II presents ten models along the tracks of the expedition's ships; eight of these models were along specific ship's tracks involved in the bottom-loss measurements. In Part III, nine additional geoacoustic models are presented. These models can be used to extrapolate bottom-loss measurements over geomorphic provinces of the sea floor or they can be used with acoustic theory to compute and thus predict bottom losses. The geoacoustic models of Part II are in Appendix A; those of Part III are in Appendix B. Each model in Appendix A is in the form of two tables with footnotes. The first table and accompanying footnotes present sediment and rock layer thicknesses and the variations with depth in the sea floor of compressional wave (sound) velocity, shear wave velocity, attenuation of compressional and shear waves, and density. The second table lists properties of the bottom water (depth, temperature, salinity, pressure, sound speed, density, and impedance).

(C) The finished geoacoustic models were forwarded to the Applied Research Laboratory (University of Texas) from January to February 1978, where they were used in studies of measurements of energy losses when sound interacted with the sea floor and in extrapolation of these measurements to adjacent areas.

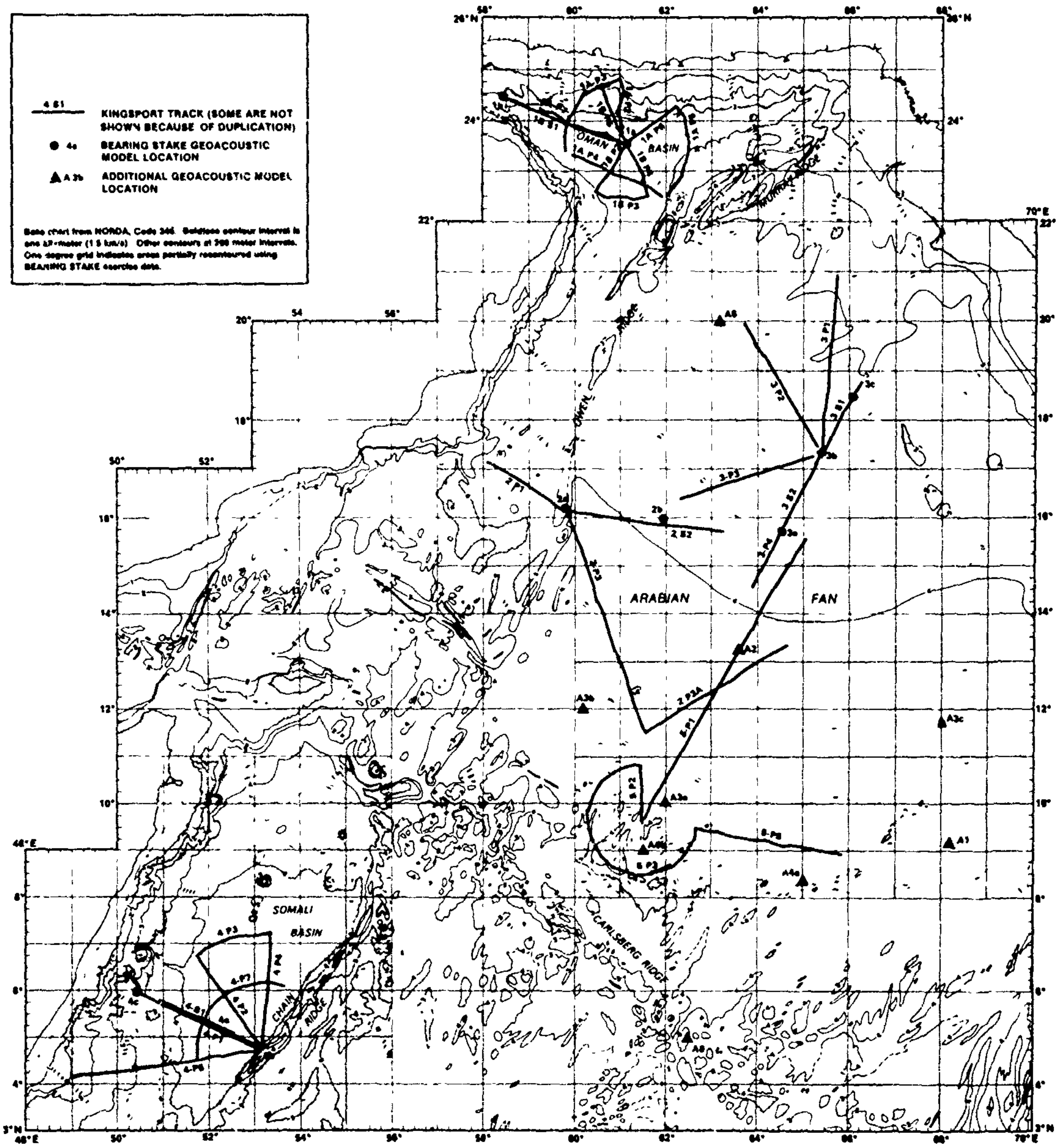

Figure 1. (C) Location chart of the BEARING STAKE expedition, northwestern Indian Ocean. (U)

GEOACOUSTIC MODELS (U)

(U) At higher sound frequencies, the acoustician may be interested in only the first few meters, or tens of meters, of sediments. At lower frequencies, information must be provided on the entire sediment column and on the properties of the underlying rock. It is this information which should be provided in the form of geoacoustic models of the sea floor.

(U) A geoacoustic model is defined as a model of the real sea floor with emphasis on measured, extrapolated, and predicted values of those properties important in underwater acoustics and those aspects of geophysics involving sound transmission. In general, a geoacoustic model details the true thicknesses and properties of the sediment and rock layers of the sea floor.

(U) Geoacoustic models are important to the acoustician studying sound interactions with the sea floor in several critical aspects: to guide theoretical studies, to reconcile experiments at sea with theory, and to predict the effects of the sea floor on sound propagation.

(U) The information required for a complete geoacoustic model should include the following properties for each layer.(It should be noted that in some cases, the state-of-the-art allows only estimates of these properties and that in other cases the information may be nonexistent)

- Properties of the overlying water mass from Nansen-cast and velocimeter lowerings
- Sediment information from cores, drilling, or geologic extrapolation: sediment types; grain-size distributions; densities; porosities; compressional and shear wave velocities, attenuations, and other elastic properties; and gradients of these properties with depth, for example, velocity gradients and interval velocities from sonobuoy measurements
- Thicknesses of sediment layers (in time) determined at various frequencies by continuous reflection profiling
- Locations, thicknesses, and properties of reflectors within the sediment body as seen at various frequencies
- Properties of rock layers, those at or near the sea floor are of special importance
- Details of bottom topography, roughness, relief, and slope, for example, as seen by underwater cameras and deep-towed equipment

Of these, the following are the basic, minimum data required for most current work in sound propagation:

- Thicknesses of layers
- Compressional wave (sound) velocity in each layer
- Sound velocity gradient through the layers
- Sound attenuation in each layer
- Density in each layer

(U) Newer and more sophisticated mathematical-computer models involving sound interaction with the sea floor also require the gradient of sound attenuation through the layers. the density gradient through the layers, the shear wave velocity and attenuation, and those gradients which can be used with density and compressional wave velocity to derive other elastic properties.

GEOLOGIC SETTING (U)

Introduction (U)

(U) This section will briefly discuss the geology of the Gulf of Oman, the Arabian Sea (including the Arabian Fan and adjacent areas), and the Somali Basin. Locations and bathymetry of these areas are indicated in figure 1. Detailed accounts of the geology of two of these areas are in recent reports of the Deep Sea Drilling Project (Arabian Fan, leg 23: Whitmarsh, et al., 1974; Somali Basin, leg 24: Fisher, et al., 1974), and the Oman Basin was discussed by White and Klitgord (1976). As these reports include data on deep structure and plate tectonics, these features will not be discussed in this document. Figures 2 through 6 show selected parts of acoustic reflection records which illustrate the relief of the sea floor, reflectors, subbottom relief, and sediment and rock thicknessess (in seconds of sound travel time) over acoustic basement in the three areas.

Oman Basin (U)

(U) The Gulf of Oman (area 1), containing the Oman Basin (figure 1). is bounded on the north by the coasts of Iran and Pakistan, on the southeast by Murray Ridge, and on the southwest by the Arabian Peninsula. White and Klitgord have published an excellent survey of the area. The material below is mostly from their report.

(U) The continental margin in the Gulf of Oman is formed by a sequence of east-west trending folds of sediment and sedimentary rock which are parallel to the coast. The folds form a series of ridges and troughs typically about 3 to 4 km wide and with ridges up to about 800 m high (figure 2). Sediments from the coast have partly covered the ridges and troughs nearest the coast, but these sediments are prevented from reaching the flat abyssal plain to the south.

(C) The major portion of the basin is filled with flat-lying turbidites which form an abyssal plain. These turbidites overlie several layers of sediments and sedimentary rocks which dip to the north at about 0.8° (figure 2). The underlying rock with a velocity greater than 4.5 km/s is probably volcanic. Measurements from the acoustic reflection records taken on the BEARING STAKE expedition and computations of thicknesses indicate that in the center of the basin at the location of geoacoustic model 1a the first layer of sediment and sedimentary rock is about 1250 m thick and layers 2 and 3 (sedimentary rock) are about 985 and 1100 m thick, respectively. As discussed in the next section (Arabian Fan), there should be a transition from soft (unlithified) sediment to rock (mudstone) at depths in the first layer between 500 and 700 m.

(U) The sediments forming the abyssal plain are typical turbidites. The cores in the area indicate that the thicker layers are typically silty clay and clayey silt (about 50 to 120 cm thick) with intercalated, thinner (about 20 cm) layers of silt. There should be hundreds of this type of layer in the 1250-m-thick first layer. These sediments entered the plain from the Persian Gulf to the west and from the Pakistan coast to the east. No channels were seen on the echo-sounder records.

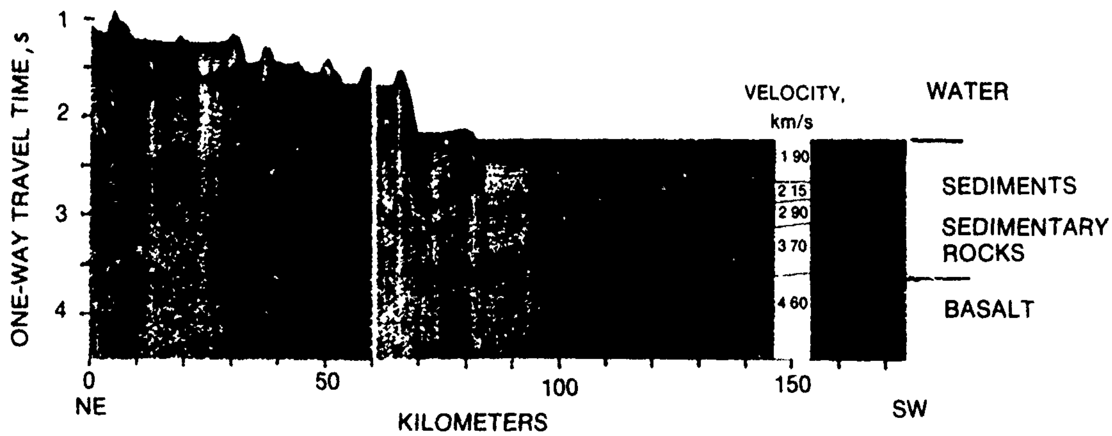

Figure 2. (U) Acoustic reflection profile from the Gulf of Oman (from White and Klitgord, 1976, figure 2). Right side (SW) is at 23°25'N, 61°35'E, left side (NE) is at 24°45'N, 62°31'E. The velocity data are from sonobuoy measurements by White and Klitgord. (U)

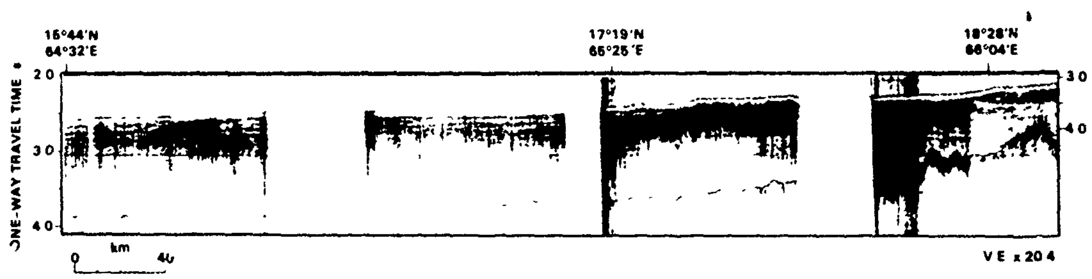

Figure 3. (C) Acoustic reflection profile in area 3, north central Arabian Fan (figure 1). The three positions noted above the top border are the positions (left to right) of geoacoustic models 3a, 3b, and 3c (3a is southwest and 3c northeast). For the left side the record shows more than 3500 m of sediments and sedimentary rocks overlying basalt; in the center the sediments and rocks are about 3300 m thick, and on the right they are approximately 1000 m thick over the basement ridge (U)

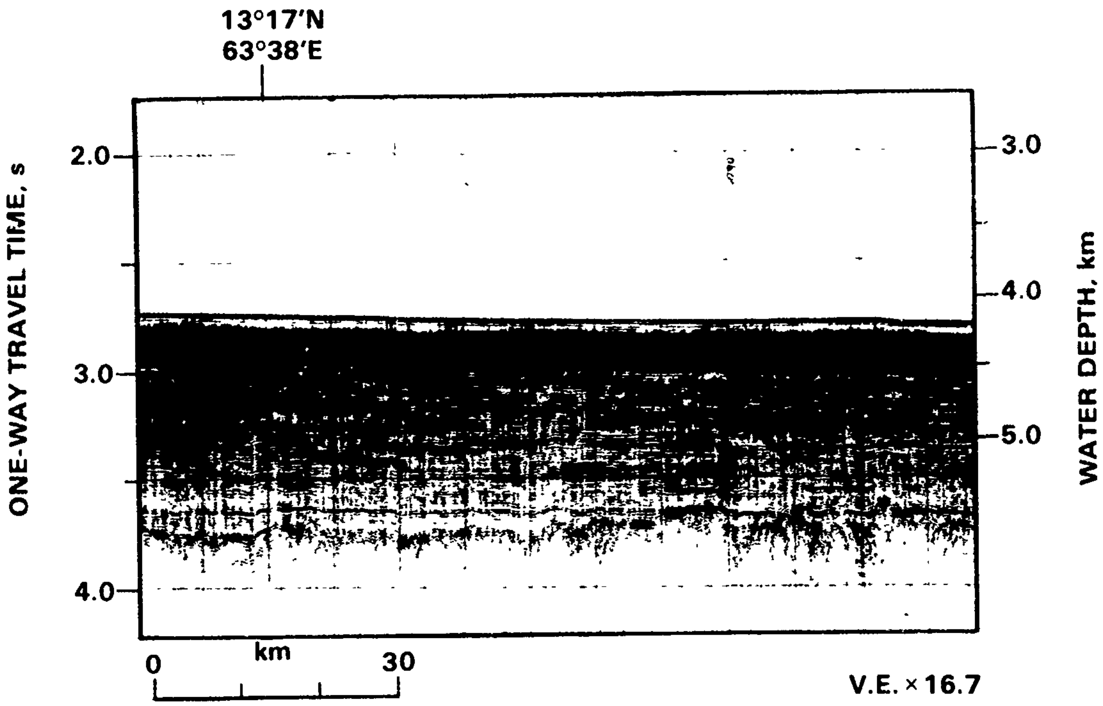

Figure 4 (C) Acoustic reflection profile, west central Arabian Fan, at the location of geoacoustic model A2 (figure 1). The record shows approximately 2400 m of sediments and sedimentary rocks overlying basalt. (U)

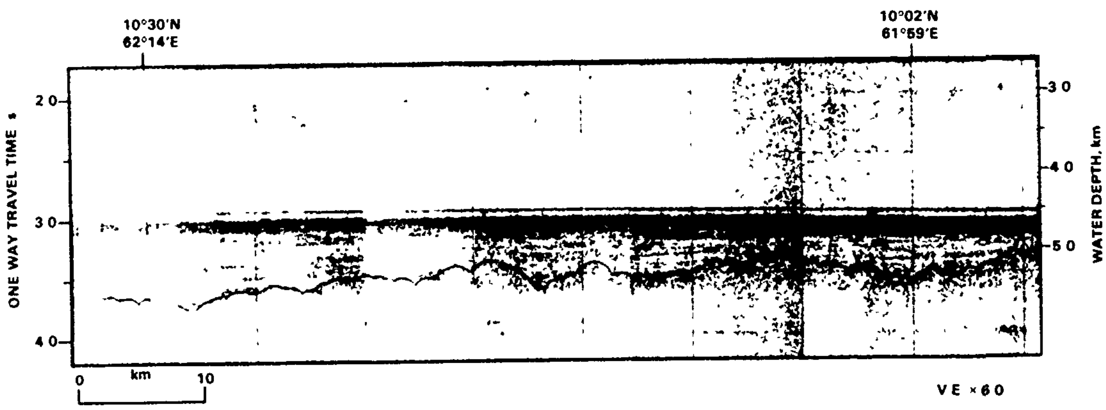

Figure 5. (C) Acoustic reflection profile near the southern end of the Arabian Fan (figure 1). Geoacoustic model A3a, near the right side or south end of the profile, has about 1000 m of sediments and sedimentary rocks overlying basalt. (U)

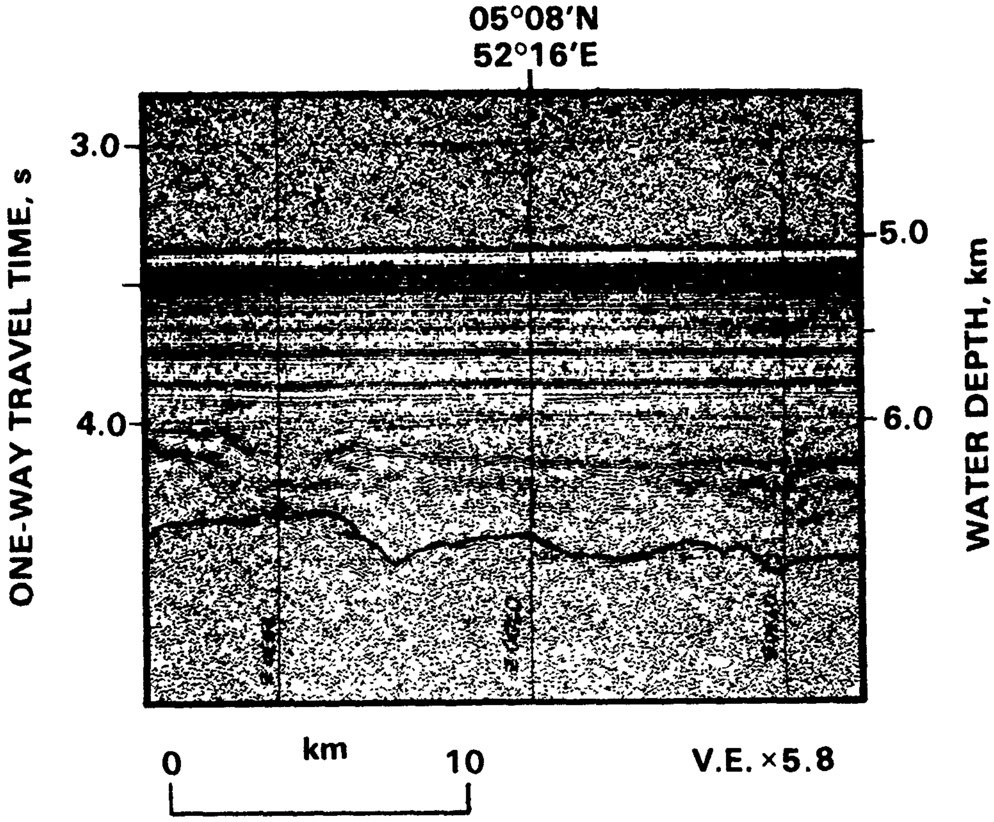

Figure 6. (C) Acoustic reflection profile near the center of Somali Basin at the site of geoacoustic model 4a (figure 1). The record shows a first layer of sediments and sedimentary rocks (about 1600 m thick) and a second layer of sedimentary rock (about 900 m thick) overlying the acoustic basement of basalt. (U)

Arabian Fan (U)

(U) Of the various names used on charts and in reports, writers prefer the term Arabian Fan (also called Indus Cone and Arabian Abyssal Plain) to include those sediments which occupy the area bounded by Murray and Owen Ridge to the north and west, Carlsberg Ridge to the south, and the Laccadive-Chagos Ridge and the subcontinent of India to the east.

(U) The Arabian Fan (area 3) has been formed mostly by mineral detritus eroded from the Himalaya Mountains. This detritus was transported down the Indus River through the Indus Canyon (incised into the continental terrace off northwest India) and deposited over an originally rough basaltic sea floor. The fan consequently slopes to the south south-west (figure 1). The sediments are very thick (over 9 km) in the northernmost part of the fan near the Indus Canyon (Naini and Talwani, 1977), and they thin to about 400 to 500 m in the southernmost end of the fan before finally pinching out against the northern edge of the Carlsberg Ridge. From the Indus Canyon in the north, the mineral particles are usually transported by turbidity currents through great leveed channels. In the northwest part of the fan, levee heights above the channels are a maximum of about 50 m, with the western levee the highest. When these turbidity currents topped the levees and left the channels, the sediments (turbidites) were deposited in the interchannel areas. This is the same mode of deposition seen in the Bengal Fan on the east side of India, in the Gulf of Alaska, and in other areas.

(C) Figure 3 illustrates a very thick sediment layer over probable basalt in the north central part of the fan. In figure 1 this profile is between geoacoustic models 3a-3c. At the site of 3a (15°44'N, 64°32'E) the sediment and sedimentary rock layer is more than 3500 m thick; it thins to about 1975 m at the site of model 3c. Figure 4 (model A2 in figure 1) illustrates a 2450-m layer of sediments and sedimentary rocks, and figure 5 illustrates thicknesses near the southern end of the fan. At site A3a (10°00'N, 61°58'E) the sediments are still thick: about 985 m. (Volume 23 of the Deep Sea Drilling Project (DSDP) contains many more illustrations of acoustic reflection records.)

(U) At site 222 of the DSDP (20°05'N, 61°31'E) in the northwest part of the fan, more than 1300 m of sediments and sedimentary rocks (mudstone) were drilled. Most of the sediment was a greenish gray silty clay or clayey silt with relatively few layers of silt, there were some carbonate sediments in the top of the section. Except in the channels (where coarser sediments might be expected) these are probably typical of sediments in the Arabian Fan.

(U) In thick terrigenous sediment sections, there is usually a transitional section through which the sediment gradually lithifies (hardens) and below which the material is a rock, usually a mudstone. This transition at site 222 occurs at about 600 m (Bachman and Hamilton, 1976). Consequently, in the various geoacoustic models with very thick first layers, the material is named as "sediment and sedimentary rock." This nomenclature implies a gradual transition from sediments to sedimentary rock at about 500 to 700 m.

(U) Reflectors in most of the Arabian Fan are probably formed by layers of silt in the interchannel areas and by silts and sands and mixtures of the two in the channels. In the thick sediment sections considered in the geoacoustic models there are many hundreds of these reflectors approximately 3 m apart. Most of them are subparallel to the sediment surface in areas away from the leveed channels.

(U) **Owen Ridge**. The western margin of the Arabian Fan is controlled by the Owen Fracture Zone and by the Owen Ridge, just west of the Fracture Zone. Owen Ridge is formed by an uplifted sediment and rock section which dips to the west, and it is bounded on the east by steep fault scarp. The DSDP drilled at site 224 on Owen Ridge at 16°33'N, 59°42'E. Volume 23 of the Initial Reports of the DSDP contain acoustic reflection records and much other information concerning this ridge.

(U) Geoacoustic model 2a is on top of Owen Ridge. Data from expedition coring and reflection records, plus information from DSDP site 224, were used to predict the model. This model shows a 100-m-thick first layer of sediment (calcareous clayey silt) over a 175-m-thick second layer (claystone, siltstone), over a 520-m-thick third layer (chalk and claystone). The acoustic basement is basalt.

(U) **Carlsberg Ridge.** Carlsberg Ridge forms the southern boundary of the Arabian Fan (figure 1). This ridge is a major feature in the northwestern Indian Ocean. It is roughly defined by the 4000-m contour on each side (to the north and south) and has many peaks and ridges at top depths between 1500 and 2000 m.

(U) The ridge is formed by basaltic lavas in the form of blocks, pillows, linear ridges, and mountains. The center of the ridge is almost bare of sediments with small, thin patches of calcareous sediments in depressions and hollows. Steep escarpments, gaps, and fissures are common; slopes range from low to vertical or even overhanging. It is an extremely rugged area of the sea floor.

Somali Basin (U)

(U) The Somali Basin (area 4) is bounded on the north by ridges essentially connecting the African continent to Socotra Island to Carlsberg Ridge (figure 1). On the west and northwest the basin is bounded by the African continent and on the east by Chain Ridge.

(U) Figure 6 illustrates the acoustic stratigraphy in the center of the basin at geoacoustic model 4a. There are three distinct layers: (1) a thick turbidite layer (sediment and sedimentary rock) about 1580 m thick which forms an abyssal plain, (2) an underlying layer of sedimentary rock about 940 m thick, and (3) the acoustic basement of basalt. The basin floor is very flat with no channels indicated on echo-sounder records.

(U) Drilling at DSDP site 234 (Fisher et al., 1974) and cores in the area indicate that the top of the first layer is calcareous ooze and clay. From cores and 3.5-kHz records, reflectors appear to be silt or silty sand about 3 m apart.

(U) On the west side of the basin (model 4c), the second layer rises toward the surface and the upper layer thins to about 970 m.

(U) Chain Ridge on the east side of the Somali Basin is a continous, basaltic ridge with a series of summit peaks. Minimum water depths along the ridge vary between approximately 1780 and 3000 m. The base of the ridge is defined by the 5000-m contour. Therefore, the ridge varies in height between about 2000 and 3200 m. Acoustic reflection records in Bunce et al. (1966) indicate about 0.13 s (one-way sound travel time) of pelagic sediment on the west side and near the top of the ridge. Computations of sediment thickness indicate a little more than 200 m of sediments, which are probably calcareous ooze and calcareous silty clay.

PART II. BEARING STAKE GEOACOUSTIC MODELS (U)

INTRODUCTION (U)

(C) Part II is concerned with geoacoustic models of the sea floor for three areas in the northwest Indian Ocean in which bottom-loss measurements were made during the BEARING STAKE expedition (January to April 1977) The three areas (figure 1) are in the Gulf of Oman (area 1B), the Arabian Sea (area 3), and the Somali Basin (area 4) off northeast Africa. Most of the necessary environmental data were collected from the USNS WILKES (T-AGS-33). Additional bathymetric data were taken by USNS KINGSPORT (T-AG-164) and USNS MIZAR (T-AGOR-11). The environmental data concerning the sea floor were furnished the writers by NAVOCEANO (Codes 3408 and 3432) and NORDA (Code 341). These data, plus information from the scientific literature, were used to formulate the models. The actual models in the form of tables with footnotes are in Appendix A. This section will discuss the methods used to derive these values and the supporting data (water-mass information, bathymetric charts and ship's tracke, and profiles of the sea floor).

(U) Appendix C is a summary of steps used to derive a geoacoustic model; it is a concise outline of the next section ("Methods and Results").

METHODS AND RESULTS (U)

Water Mass Data (U)

(U) To compile a geoacoustic model it is necessary to have oceanographic cast data to determine (1) sound velocity as a function of water depth (to extrapolate to sound velocity in the bottom water), (2) water density in situ as a function of water depth (to obtain the density of the bottom water), and (3) corrections to echo sounder depth to obtain true depth. For this expedition, echo sounders were set for a water velocity of 1500 m/s.

(U) The basic sound velocity, salinity, temperature, and depth information from oceanographic cast data, taken from the USNS WILKES (20 stations), was obtained from Code 3432 (R.S. Rushton), Naval Oceanographic Office. These data were used by Code 7143 (J.G. Colborn), Naval Ocean Systems Center (NOSC), to compute pressure, density, and corrections to apply to an echo-sounder depth (sounder set at 1500 m/s) to obtain true depth. Copies of the basic data set were sent to other interested parties. Both sets of station data are available from Code 531 (Attn. Hamilton or Bachman), NOSC.

(U) In area 1 (Gulf of Oman), the oceanographic cast data varied too greatly to average all the casts. Consequently, those casts nearest the locations of the models were favored. For geoacoustic model 1a, two casts (15 and 16) in the deep central basin were used to extrapolate data to the bottom. At the location of geoacoustic model 1b, in the hills west of the central basin, cast station 2 was used. The station cast data were used to obtain a correction for true depth, but use of Matthews' tables (area 38) will yield true depths within 1 to 3 m of the expedition data.

(U) For area 3 over the Arabian Fan (sometimes called the Indus Cone, Indus Fan, or Arabian Abyssal Plain), six oceanographic cast stations of USNS WILKES (8 through 13) were averaged for extrapolation of data to the sea floor. Matthews' tables (area 38) were used to correct echo-sounder depths to true depths, as these corrections did not significantly differ from those computed from cast data.

(U) In the Somali Basin (area 4), four oceanographic cast stations of USNS WILKES (17 through 20) were averaged for extrapolation of data to the sea floor. In this area, no section of Matthews' tables was appropriate; therefore average corrections from the station data were used to correct echo-sounder depths to true depths. These corrections were as follows:

Echo-Sounder Depth, m	Correction, m (add to echo-sounder depth)	Echo-Sounder Depth, m	Correction, m (add to echo-sounder depth)
1000	5	3500	6
1500	4	4000	13
1750	3	4500	23
2000	2	5000	35
2500	1	5100	37
3000	2		

Bathymetric Charts and Ships' Tracks (U)

(C) A major requirement in analyses of acoustic, geologic, and geophysical data taken at sea is a good, small-scale, bathymetric chart on which the tracks of the expedition's ships are plotted with date-time notations along the tracks. After soundings have been plotted along the ships' tracks, the original contours should be corrected as a result of the expedition's soundings. This requirement for BEARING STAKE was satisfied as follows.

(U) The most recent charts, contoured by Naval Oceanographic Office personnel in 1974 and 1975, were obtained from Code 341 (R.J. Busch), NORDA, at plotting sheet size for the area occupied by the expedition ships. These charts were contoured at 20-m intervals (to 100 m) in shallow water, then at 200 m, and then at 200-m intervals at depths greater than 200 m. These contours were from depths determined by echo sounders set for a water velocity of 1500 m/s, and were uncorrected for sound velocity.

(C) Using the above charts, the tracks and soundings of USNS KINGSPORT, USNS MIZAR, and USNS WILKES were plotted in areas of interest for the BEARING STAKE expedition. These data and records, controlled by satellite navigation, were forwarded by D.F. Fenner (Code 341, NORDA). The soundings were plotted along the tracks and the basic contours corrected. The resulting five charts with KINGSPORT tracks in the five areas of interest were then drafted in ink, reproduced at one-to-one size and one-quarter size, and forwarded to interested parites. Copies of these charts may be obtained from Code 531 (Attn. Hamilton or Bachman), NOSC. Figure 1 is a large-scale version of several reduced charts. Copies of this figure may also be obtained from Code 531, NOSC.

(U) The KINGSPORT tracks not plotted on the charts were omitted to avoid confusion with plotted tracks. Omitted tracks can be plotted by interested readers with basic data from Code 341 (Attn D.F. Fenner), NORDA.

Profiles of the Sea Floor (U)

(U) In some acoustic studies it is necessary to have profiles of the sea floor along the track of a ship or aircraft involved in acoustic measurements. These profiles show the relief or depth of the sea floor plotted against distance along the track.

(C) For BEARING STAKE, data for profile constructions were forwarded by D.F. Fenner (Code 341, NORDA). These data for the KINGSPORT included location as a function of date and time, corrected echo-sounder depth, and distance along the tracks in nautical miles. Distance was converted to kilometers, and computer programs were devised for plotting profiles at various scales.

(U) Thirty-five profiles for KINGSPORT propagation runs were drawn by computer. Additionally, three KINGSPORT ship-aircraft profiles and 14 aircraft profiles were drawn. These profiles were duplicated and forwarded to persons who required them in data analyses. Copies of all profiles may be obtained from R.T. Bachman (Code 5311, NOSC). An example from each of the three areas is included as figures 7, 8, 9.

Compressional Wave (Sound) Velocity (U)

(U) There are two important elements in the derivation of a curve and equation for compressional wave velocity (hereafter called sound velocity or velocity) as a function of depth in the sea floor: (1) a value for velocity at the sediment surface (designated as V_0) and (2) the variations of velocity with depth in the sea floor.

(U) The value of sound velocity at the sediment surface can be predicted from tables or corrected to in situ from laboratory measurements in core samples (Hamilton, 1971). In the present case, sediment velocity measurements were made in the laboratory aboard USNS WILKES by NAVOCEANO personnel and forwarded by J.H. Kravitz (Code 3408, NAVOCEANO). These measurements can be corrected to in situ by making full corrections for temperature and pressure from tables for the speed of sound in sea water (NAVOCEANO SP 68, 1966) or more easily by multiplying the velocity in the bottom water (from cast data) by the velocity ratios, i e., sediment velocity in the laboratory at a certain temperature divided by sound speed in sea water at 1-atmosphere pressure and the same temperature. Salinity is assumed to be the same in sediment pore water and in bottom water. This ratio remains the same in laboratory or at various water depths in situ.

(U) In the footnotes to the tables for each geoacoustic model are listed the sound velocity, density, and other properties for the first meter of sediments in the central abyssal plain in area 1 and for the first 3 m in areas 3 and 4.

(U) In area 1 (Gulf of Oman), two cores were taken along the insonified line in the flat abyssal plain and one core was taken near the end of the line in the hills. In the abyssal plain there is an alternation of higher porosity, lower velocity mud (silt-clay) layers (velocity ratio of 0.98) about 0.8 m thick with lower porosity, higher velocity silt layers (velocity ratio of 1.07) about 0.2 m thick. After discussions with acousticians, it was decided to include as surface or "Sfc" in the main table (geoacoustic model 1a) a composite of the first meter for these low frequencies. The resulting "Sfc" velocity ratio is

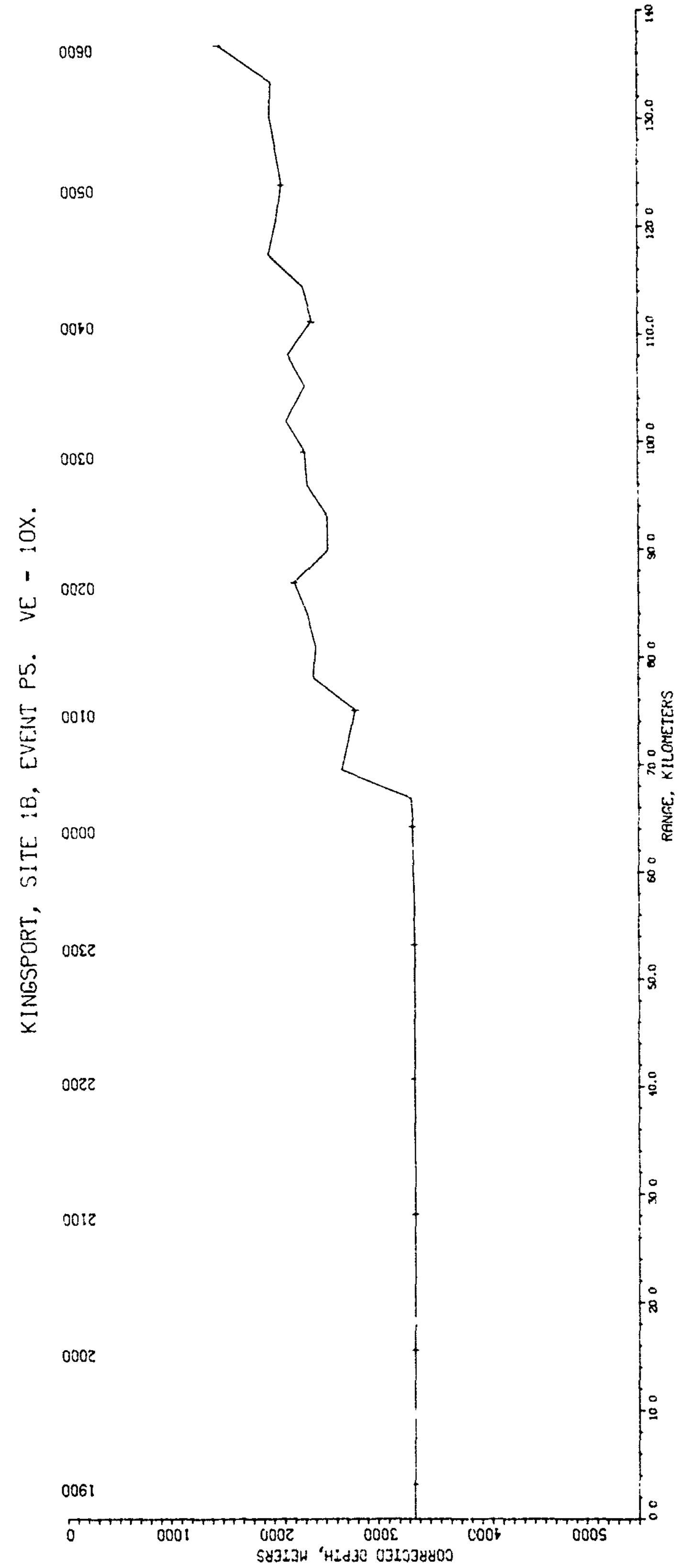

Figure 7. (U) Profile of the sea floor in the Gulf of Oman (area 1B) along USNS KINGSPORT track P5 (figure 1). (U)

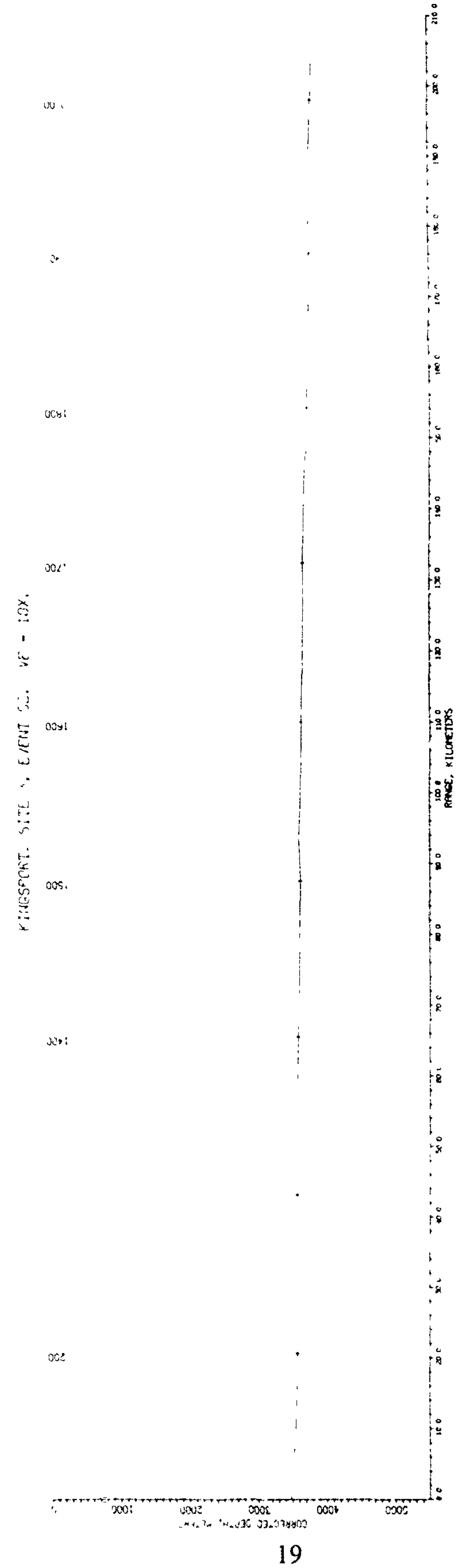

Figure 8. (U) Profile of the sea floor in the Arabian Sea (area 3) along USNS KINGSPORT track S2 (figure 1). (U)

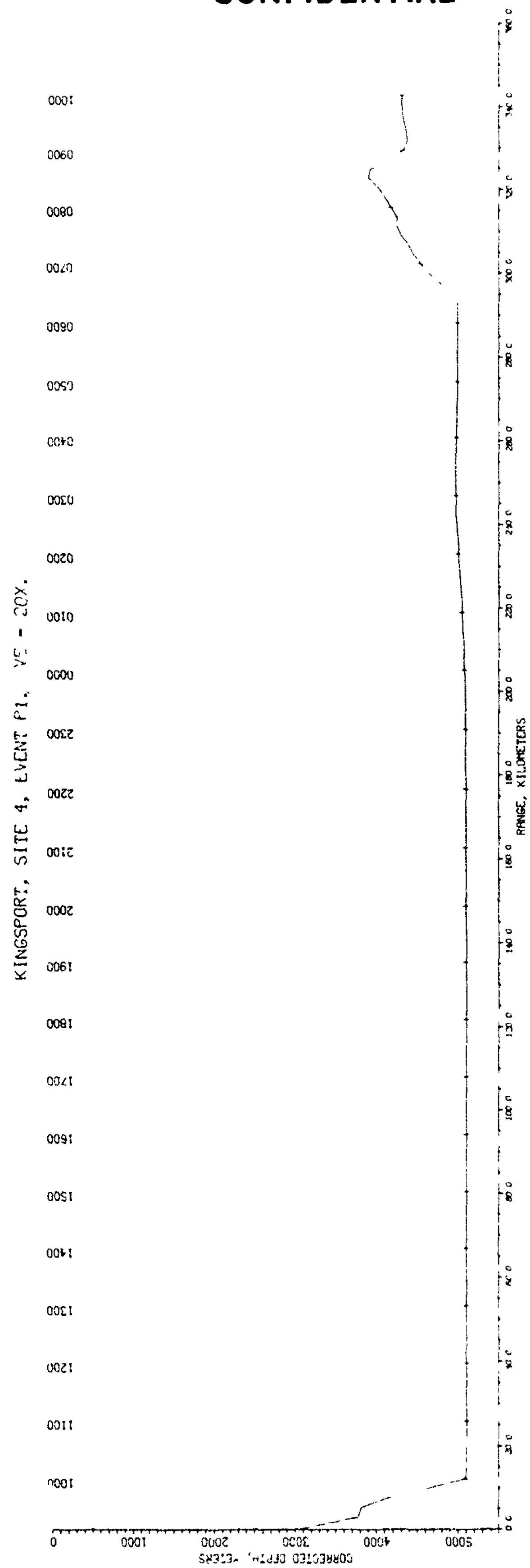

Figure 9. (U) Profile of the sea floor in the Somali Basin (area 4) along USNS KINGSPORT track P1 (figure 1). (U)

1.00. In this way both of the differing layers are included and averaged. To have listed only the lower velocity mud as "Sfc" would have disregarded the silt layer. In any event, the details of the first layer are given in the footnotes and the composite is in the main table. At higher frequencies an alternative would have been to alternate the first two layers of the first meter to any desired depth. In this case, the velocity and other values would change according to their gradients. Data from the single core in the hills (near the location of the model) were used for sediment surface properties for geoacoustic model 1b (velocity ratio of 0.98).

(U) In areas 3 and 4, the first layer of lower velocity mud (silt-clay) is thicker (assumed to be about 2.8 m) with a velocity ratio of 0.98. Reflectors at depths of about 2.5 to 3 m can be seen on the 3.5-kHz records in both areas, although only one core in area 3 was long enough to core the material of the reflector. Based on the 3.5-kHz records and the higher velocity and density material cored, a 0.2-m layer of sand-silt-clay with a velocity ratio of 1.06 is assumed for a generalized model. Thus, in a 3-m section there is a top layer of silt-clay (2.8 m) and a sand-silt-clay layer (0.2 m). The properties of the composite 3-m section (with a velocity ratio of 0.99) are listed in the main tables for models 3a, 3b, 3c, 4a, and 4c. The detail for this 3-m section is included in the footnotes; these detailed layers can be alternated to any depth with numerical values changing according to their gradients.

(U) Having established values of velocity at the sediment surface, the next step was to establish general curves for velocity as a function of depth.

(C) No usable sonobuoy measurements of layer velocities were made in the Gulf of Oman during the BEARING STAKE expedition; consequently, data from the literature and other similar areas had to be used to establish a curve for velocity as a function of depth in the sea floor. White and Klitgord (1976) have presented the results of an excellent acoustic reflection survey in the Gulf of Oman. Their survey also included sonobuoy determinations of sediment and rock layer velocities (figure 2).

(U) White and Klitgord (1976) noted that averaged values of velocity gradients for 13 largely turbidite areas (Hamilton et al., 1974) accurately characterized their data (see figure 10). Since Hamilton's publication of averaged velocity gradients for 13 areas in 1974, data on four additional areas have become available (Hamilton et al., 1977). The averaged data from these 17 areas were used for the thick first layer of sediments and sedimentary rock in the Gulf of Oman.

(U) For the Gulf of Oman, the equations for instantaneous velocity (V_p) and mean velocity ($\bar{V}_p$) between the sediment surface and any given time in kilometers per second as a function of one-way sound travel time (t) in seconds or depth (D) in kilometers are

$$V_p = 1.515 + 2.028t - 0.848t^2 \quad (1)$$

$$\bar{V}_p = 1.515 + 1.077t - 0.434t^2 \quad (2)$$

$$V_p = 1.515 + 1.292D - 0.611D^2 + 0.141D^3 \quad . \quad (3)$$

(U) Figure 11 illustrates velocity as a function of depth in the first layer (equation 3). The curve has been forced through a suface value (1.515 km/s) derived from coring data corrected to in situ values as discussed above.

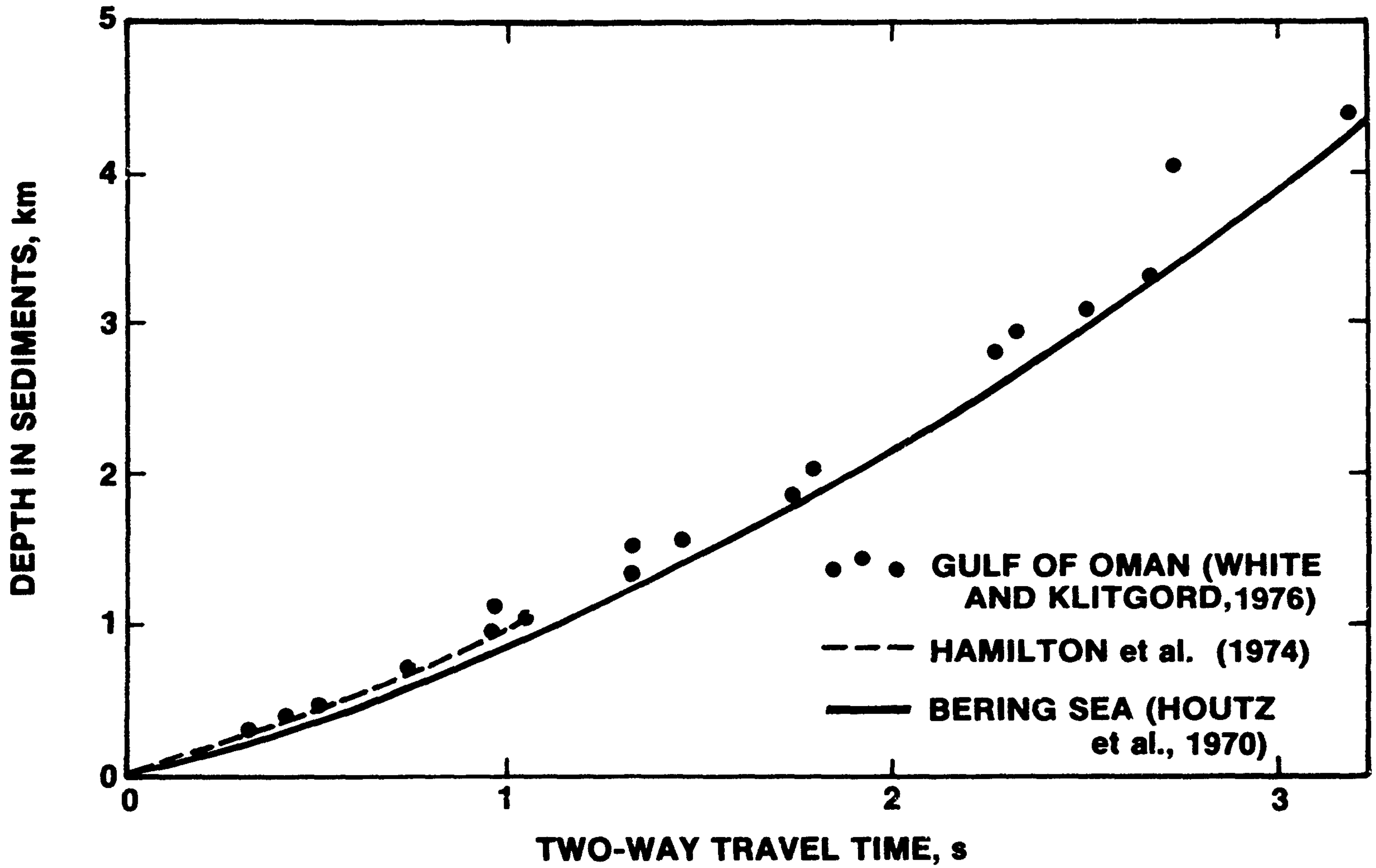

Figure 10. (U) Depth in the sea floor as a function of travel time of sound in the flat abyssal plain in the Gulf of Oman (from White and Klitgord, 1976, figure 3). The data from Hamilton et al. (1974) represent an average curve based on velocity gradients in 13 areas of mostly turbidites. (U)

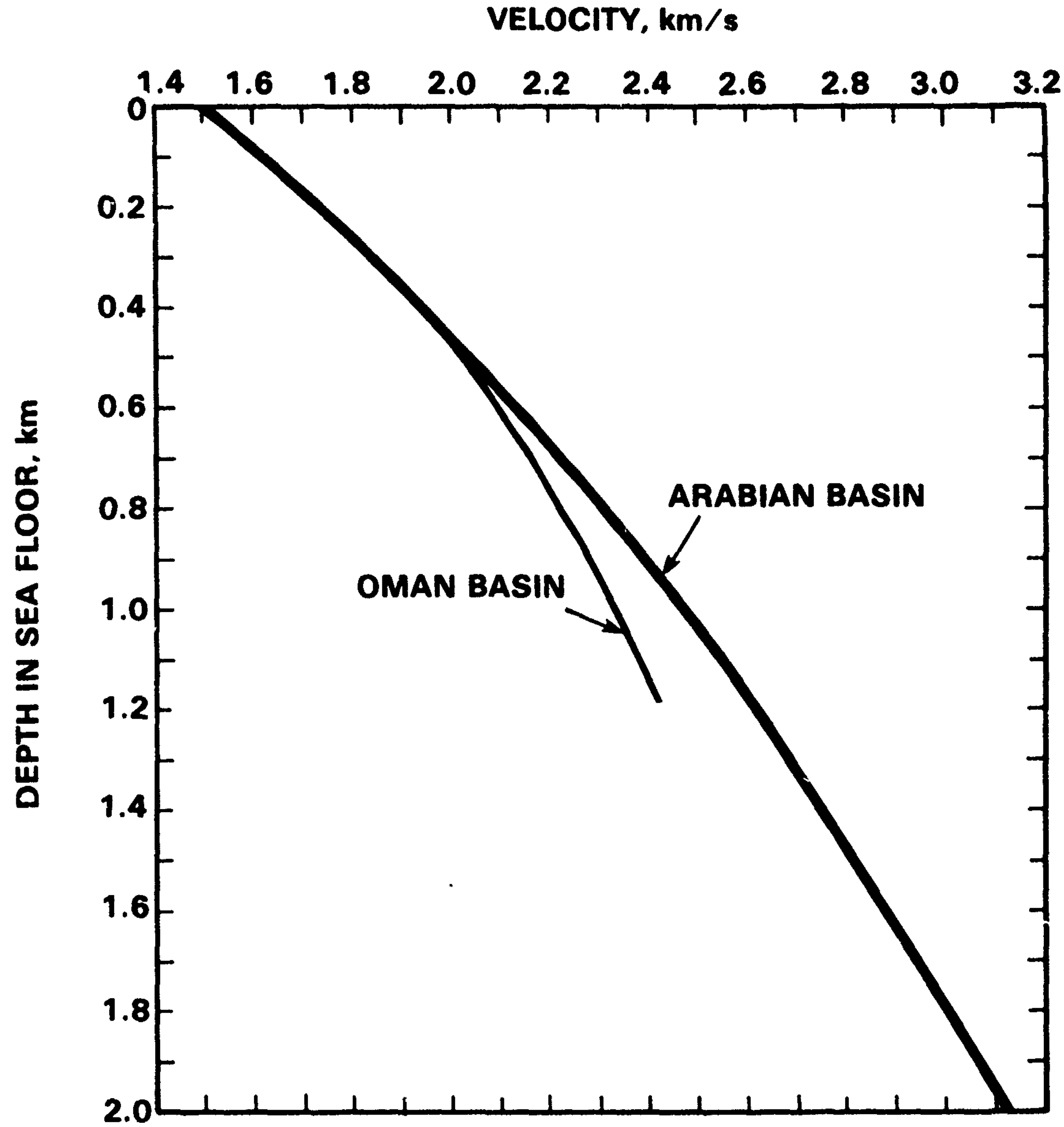

Figure 11. (C) Sound velocity as a function of depth in the sea floor in the Oman and Arabian Basins. The Oman Basin curve is based on averaged data from 17 areas of mostly turbidites (Hamilton et al., 1977), and the curve for the Arabian Basin is based on BEARING STAKE expedition sonobuoy measurements. (U)

(U) The sonobuoy measurements of White and Klitgord (1976) were from wide-angle reflections in the upper layers and from refractions in the tops of deeper layers. The values of velocity in the lower layers of rock in the Gulf of Oman (geoacoustic model 1a) were selected from White and Klitgord and from refraction measurements in this area by Closs et al. (1969). This established values of velocity at the tops of the layers. Mean layer velocities and velocities in the bottoms of the layers were estimated by using gradients at these depths from data of Naini and Talwani (1977) for the Arabian Fan to the southeast.

(C) Sonobuoy measurements of interval velocities in sediment and rock layers in the Arabian Fan during BEARING STAKE were sufficient to establish a curve and equation for velocity as a function of sound travel time and depth in the sea floor. Eight sonobuoys provided about 40 measurements. The data were reduced as discussed by LePichon et al. (1968), Houtz et al. (1968, 1970), Houtz (1974), and Hamilton et al. (1974, 1977).

(U) The data and regression curve for velocity as a function of one-way travel time of sound for the Arabian Fan are in figure 12. The curve for velocity as a function of depth in the sea floor is shown in figure 11 with that for the Gulf of Oman. The curves for the Arabian Fan have been forced through an average value of velocity at the sediment surface (1.510 km/s) derived from the probable velocities in the areas of the eight sonobuoy stations (using a velocity ratio of 0.99). The equations for V_p and $\bar{V}_p$ in kilometers per second as a function of t in seconds and V_p as a function of D in kilometers are

$$V_p = 1.510 + 1.863t \tag{4}$$

$$\bar{V}_p = 1.510 + 0.932t \tag{5}$$

$$V_p = 1.510 + 1.20D - 0.253D^2 + 0.034D^3 \ . \tag{6}$$

(U) As a velocity ratio of 0.99 was used for all models on the Arabian Fan, each model has a slightly different V_o at the sediment surface. These V_os were substituted into equations 4 through 6 for individual model equations.

(C) Figure 12 also shows a regression curve from Naini and Talwani (1977) for sonobuoy measurements in the Arabian Fan. Although their curve was not forced through a value of velocity at the sediment surface, their linear regression curve is very close to that for the BEARING STAKE data. Both independent sets of data support each other. The velocity of 5400 m/s for basalt under the Arabian Fan is from a refraction station over the southeast fan by Francis and Shor (1966).

(U) Four data points from sonobuoy measurements on the BEARING STAKE expedition in the Somali Basin (area 4) were insufficient to establish a relationship for velocity as a function of depth. Consequently, this equation for the Somali Basin was based on the average curve for 17 areas (discussed above for the Gulf of Oman). For the flat, central portion of the Somali Basin, the equations were forced through the in situ sediment surface velocity of 1.528 km/s (velocity ratio of 0.99). The equations for this area are

$$V_p = 1.528 + 2.028t - 0.848t^2 \tag{7}$$

$$\bar{V}_p = 1.528 + 1.077t - 0.434t^2 \tag{8}$$

$$V_p = 1.528 + 1.25D - 0.45D^2 + 0.0568D^3 \ . \tag{9}$$

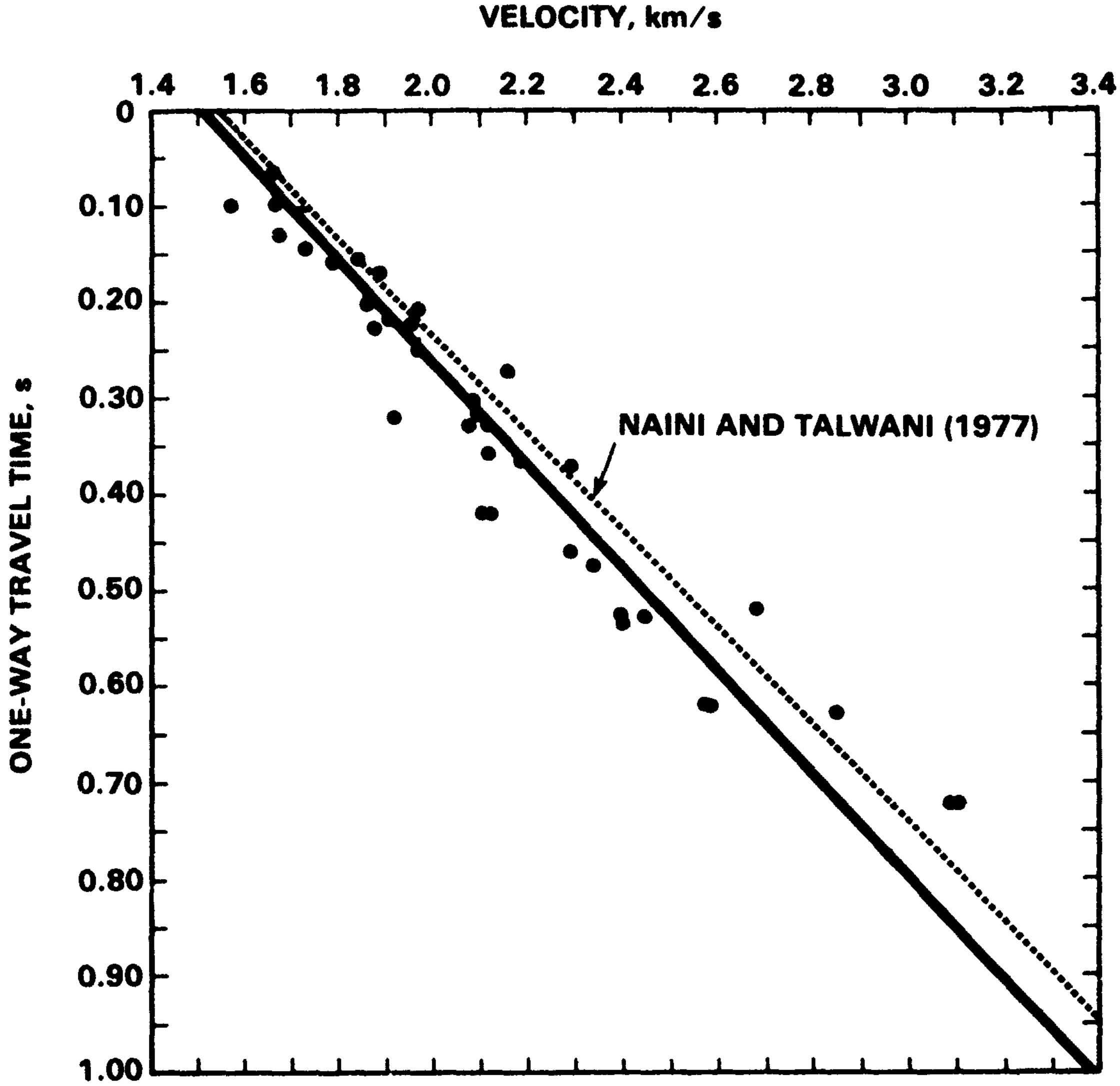

Figure 12. (C) Sound velocity as a function of one-way travel time of sound in the Arabian Fan. The data points (solid circles) and the solid line are based on BEARING STAKE expedition sonobuoy measurements. The dashed line (Naini and Talwani, 1977) is based on sonobuoy measurements in the Arabian Fan by Lamont-Doherty Geological Observatory. The dashed line was not forced through the same velocity value as the solid line at the sediment surface (time = 0). (U)

(U) Geoacoustic model 4b is on Chain Ridge. No cores were taken on the ridge during the expedition. The sediment type is assumed to be foraminiferal ooze, and the velocity ratio is assumed to be 1.01 (unpublished measurements in this type of material). This yields a sediment surface velocity of 1.540 km/s, which was used in the above equations as V_0 (instead of 1.528 km/s).

(U) Geoacoustic model 4c is for the lower slopes of the continental rise, west of the flat, central Somali Basin (figure 1). No cores were taken in this area; therefore, a velocity ratio of 0.99 was estimated from similar sediments. This velocity ratio yielded a sediment surface value of 1.510 km/s, which was used as V_0 in equations 7 through 9.

(U) The velocity for basalt in the Somali Basin (5300 m/s) is based on measurements listed in Francis et al. (1966), Vinogradov and Udintsev (1975), Schreiber et al. (1974), and Simpson et al. (1974). Information in Bunce et al. (1967) and Schlich et al. (1972) was also used in construction of the models in the Somali Basin.

Compressional Wave (Sound) Velocity Gradients (U)

(U) A recent study of sound velocity as a function of depth in the sea floor contained a resume' of velocity gradients (a) in meters per second per meter (s^{-1}) as a function of one-way sound travel time (t) in seconds for 17 areas of mostly turbidite sediments (Hamilton et al., 1977, figure 7, p. 3010). The regression equation for these data was

$$a = 1.316 - 1.117t \quad . \qquad (10)$$

This equation can be used to estimate velocity gradients in turbidite areas after the sound travel time is measured from acoustic reflection records.

(U) As previously discussed, averaged data from the 17 areas were used to determine velocity as a function of depth and sound travel time for the Gulf of Oman and the Somali Basin. The relationship for velocity as a function of depth for these two areas is indicated in equations 3 and 9. The equation for the Arabian Fan (equation 6) was based on sonobuoy measurements of the expedition. These equations can be used to compute linear velocity gradients between any two depths in the sea floor. For the three areas, examples of velocity gradients computed from equations 3, 6, and 9 are

Area	Velocity Gradients, s^{-1} Depth Intervals, m			
	0-10	0-100	100-200	200-300
Gulf of Oman	1.30	1.23	1.12	1.01
Arabian Fan	1.20	1.18	1.12	1.08
Somali Basin	1.25	1.21	1.11	1.04

(U) The velocity gradients in the Gulf of Oman (geoacoustic model 1a) and the Somali Basin (geoacoustic model 4a) are essentially the same since they were derived from the basic data for the 17 areas; small differences are the result of slightly different equations relating velocity and depth. Inspection of the above table and data in figure 11 indicates that velocity gradients in the upper levels of the Arabian Fan are quite close to those in the Gulf of Oman and Somali Basin. The gradients in the Arabian Fan were determined independently and are not included in the averages for the 17 areas. Thus the new data strongly support the previously published average data.

Computations of Sediment and Rock Layer Thicknesses (U)

(U) There are two common ways to compute the true thickness of a sediment or rock layer. The first method requires the one-way travel time of sound through the layer and the mean velocity in the layer (usually determined from sonobuoy measurements). The second method requires the one-way sound travel time, the velocity of sound at the surface of the layer, and the velocity gradient.

(U) Two-way travel time of sound through a layer (reflection time) can be measured directly from the acoustic reflection record, e.g., figures 3 through 6. The data in figures 3 through 6 were divided by two to obtain one-way travel time and are listed in each geoacoustic model under "Thickness, s" in the main table.

(U) The values of one-way travel time (t) were used in the first method with the equations for mean velocity as a function of one-way travel time (equations 2, 5, and 8) to determine mean velocity ($\bar{V}_p$). The thickness (h) of a layer was then computed ($h = \bar{V}_p t$). These values are listed under "Thickness, m" in the main table for each model.

(U) The second method was used to obtain layer thicknesses in some very thin sediment layers in which the sediment surface velocity (V_o) was known from cores and the velocity gradient (a) was estimated from equation 10. One-way travel time was measured as above. Thickness was then computed with the equation $h = V_o(e^{at} - 1)/a$. For some lower sedimentary rock layers in areas 1 and 4, the velocities at the tops of the layers were established from seismic refraction measurements found in the literature (the equivalent of V_o). Linear velocity gradients were estimated from Naini and Talwani (1977), and one-way travel time was measured as before. Thickness was then computed as above for thin sediment layers. These data also established layer mean velocities (at the midpoint of the layer) and velocity at the bottom of the layer.

Shear Wave Velocity (U)

(U) The velocity of shear waves in the first layer of sediments and sedimentary rocks was determined by the relationship between shear and compressional waves from an unpublished study. The basic information on shear wave velocity as a function of depth in silt-clays came from Hamilton (1976d). In that study, three linear regression equations defined the data between the sediment surface and depths to 650 m. Averaged data from 17 areas of mostly turbidites were used to define compressional wave velocity as a function of depth (unpublished data). When these two data sets were linked at common depths, regression equations were determined to link compressional and shear wave velocities to depths of about 600 to 700 m. The resulting curves are shown in figure 13. The linear curve between compressional velocities of about 2.15 and 3.4 km/s was extrapolated on very little, selected data.

(U) The regression equations for compressional wave velocity (V_p) and shear wave velocity (V_s) in kilometers per second for silt-clay sediments and sedimentary rocks such as mudstones and shale are

$$V_p = 1.512 \text{ to } 1.555 \text{ km/s}$$

$$V_s = 3.884V_p - 5.757 \tag{11}$$

$$V_p = 1.555 \text{ to } 1.650 \text{ km/s}$$

$$V_s = 1.137V_p - 1.485 \tag{12}$$

$$V_p = 1.650 \text{ to } 2.150$$

$$V_s = 0.991 - 1.136V_p + 0.47V_p^2 \tag{13}$$

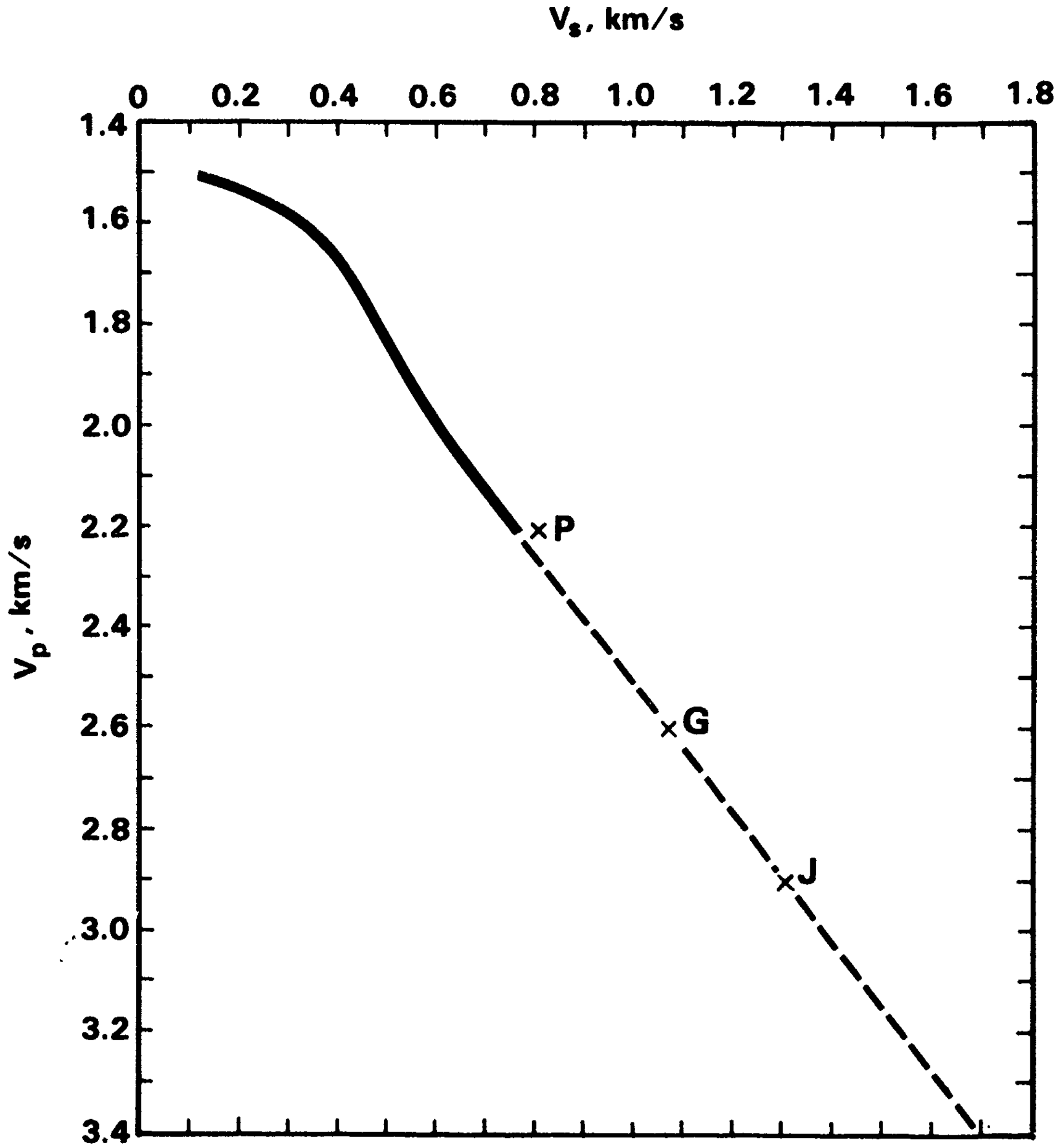

Figure 13. (U) Compressional wave velocity (V_p) as a function of shear wave velocity (V_s) in silt-clay, turbidites, mudstone, and shale. Data are from the literature. The symbols P, G, and J represent Pierre shale (McDonal et al., 1958), Grayson shale (Geyer and Martner, 196?), and data from a deep bore hole in Japan (Yamamizu, unpublished data). (U)

$$V_p = 2.150 \text{ to } 3.4 \text{ km/s}$$

$$V_s = 0.78V_p - 0.962 \quad . \tag{14}$$

(U) When the sediment surface's compressional velocity was less than 1.51 km/s, the shear wave velocity was determined with a V_p/V_s ratio of 13.0 (the ratio at the water-sediment interface predicted by the unpublished study previously noted). At compressional wave velocities greater than 3.4 km/s, a V_p/V_s ratio of 2.0 was used.

(U) The data illustrated in figure 13 and defined in equations 11 to 14 apply to terrigenous silt-clay sediments and sedimentary rocks. The same equations were used to predict shear wave velocity in calcareous ooze and pelagic clay because of lack of sufficient data for these sediment types.

(U) The equations of Christensen and Salisbury (1975) from measurements in basalts drilled by the Deep Sea Drilling Project were used to predict shear wave velocities in basalts, given values of compressional velocity from the literature sources noted above. The findings of Christensen and Salisbury are illustrated in figure 14. An equation computed by the writers from these data is

$$V_s = 0.531 + 0.2077V_p + 0.0374\,V_p^2 \text{ km/s} \tag{15}$$

(U) When the rock type was considered to be limestone, a V_p/V_s ratio of 1.90 (unpublished study) was used with the literature value for compressional wave velocity to predict the shear wave velocity.

(U) In the detailed models for the 0- to 3-m depth intervals in the sediments, e.g., model 3a, Appendix A, the value of V_s at the bottom of the silt-clay layer was established by using a variation of an equation by Hamilton (1976d, equation 2, p. 990): $V_s = V_{s,sfc} + 4.65D$, where V_s is in meters per second and D is depth in meters.

Attenuation of Compressional Waves (U)

(U) The predicted values for the attenuation of compressional waves for the sediment surface in the models were based on published relationships between attenuation and sediment porosity and mean grain size (Hamilton, 1972, 1974, 1976a). In these reports attenuation of compressional waves (αp) in decibels per meter was related to frequency (f) in kilohertz through a constant (k_p) in the equation

$$\alpha_p = k_p f \quad . \tag{16}$$

(U) The case was made that attenuation was approximately related to the first power of frequency. Thus the only variable in equation 16 is the constant k_p. This constant varies with sediment type and is related to porosity and mean grain size (figures 15 and 16). The values of porosity from coring data were used to enter the equations for k_p as a functon of porosity (n) as a decimal fraction (Hamilton, 1972):

for porosities between 0.52 and 0.65

$$k_p = 3.3232 - 4.89n \tag{17}$$

for porosities between 0.65 and 0.90

$$k_p = 0.7602 - 1.487n + 0.78n^2 \quad . \tag{18}$$

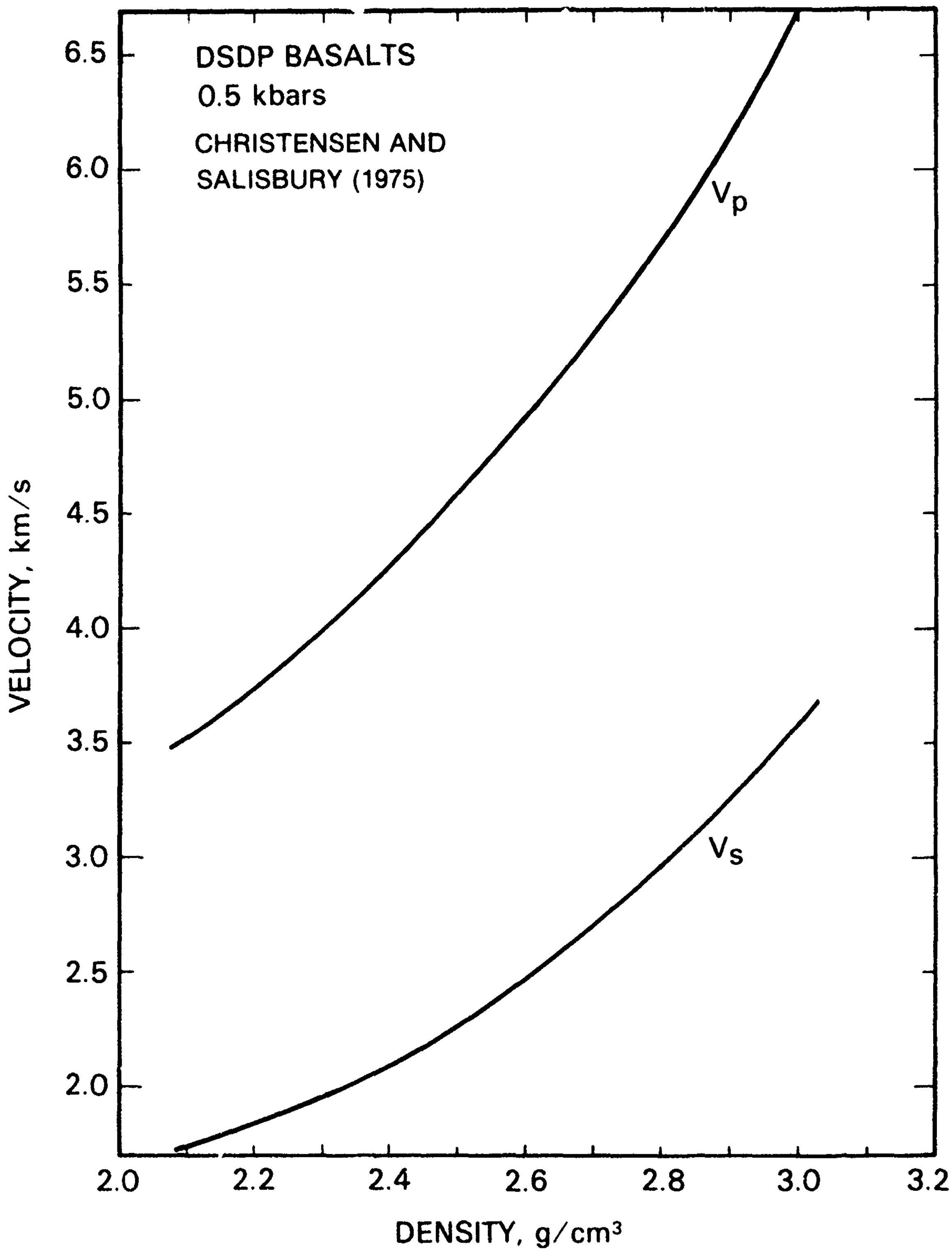

Figure 14. (U) Compressional wave velocity (V_p) and shear wave velocity (V_s) as a function of density in basalts recovered from Deep Sea Drilling Project sites (from Christensen and Salisbury, 1975). (U)

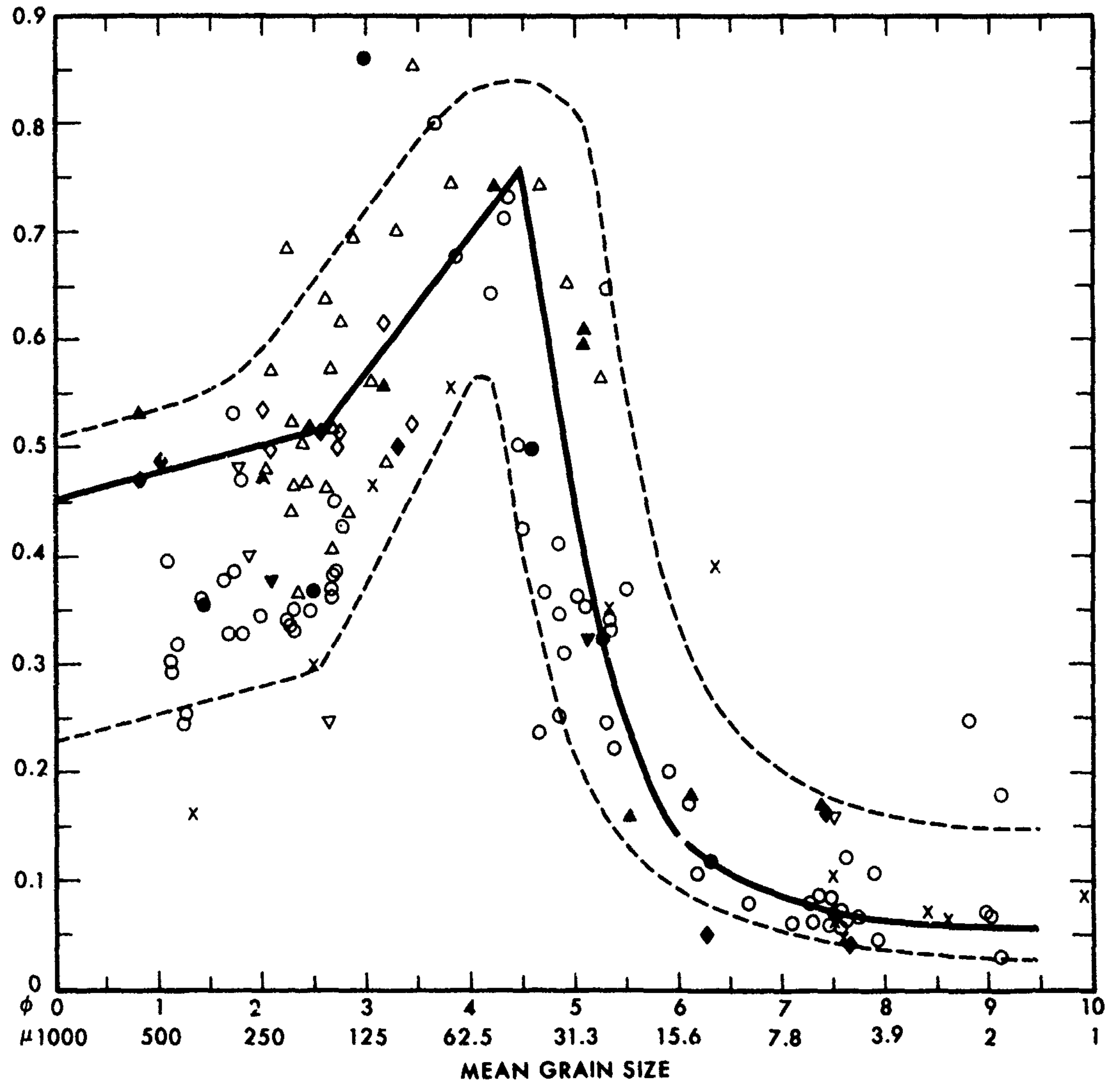

Figure 15. (U) Surface sediment mean grain size as a function of the constant k (attenuation of compressional waves in dB/m $\alpha_p = kf_{kHz}$). The solid lines are regressions on the better data; the dashed lines are probable maximum and minimum values (from Hamilton, 1972, figure 3). For additional information and regression equations see the cited report. (U)

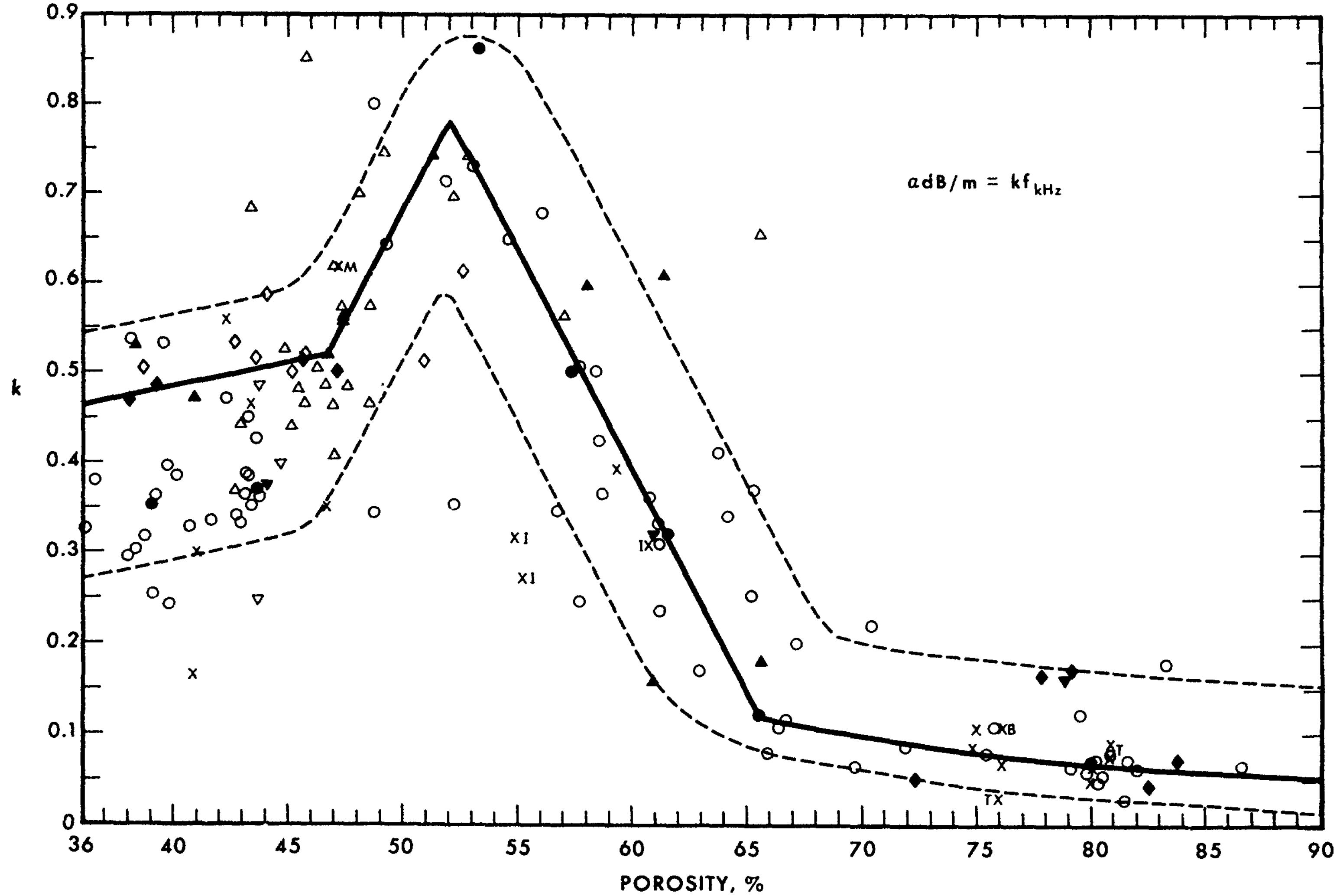

Figure 16. (U) Sediment surface porosity as a function of the constant k (attenuation of compressional waves in dB/m, $\alpha_p = kf_{kHz}$). The solid lines are regressions on the better data; the dashed lines are probable maximum and minimum values. See Hamilton (1972 and 1976a) for additional information. (U)

(U) The values from these equations were listed in the main tables as surface (Sfc) values; these values are recommended for first-trial use by acousticians in reconciling experiments with theory. However, as there is much scatter in the data, predictions must include a probable range based on the dashed lines above and below the regression curves (figures 15 and 16) (Hamilton, 1972, p. 635 and figure 3). Consequently in the main table for each model there are three values listed under k_p. The center value is recommended for first-trial use by acousticians in reconciling experiments with theory; the left value is probable minimum; and the right value is probable maximum.

(U) It has been noted that the equations relating mean grain size and k_p (Hamilton, 1972, figure 3) will frequently yield lower values of k_p than will porosity for the same sediment. Thus, the expected lower limit for k_p in higher porosity sediments in the diagram for mean grain size as a function of k_p (figure 15) is about 0.03.

(U) When low-frequency sound is transmitted through sediment and sedimentary rock layers of the sea floor, sound energy is lost through a number of mechanisms. The more important of these have been excellently summarized by Sheriff (1975). In addition to spreading losses, some of these are as follows:

1. Intrinsic absorption or attenuation: The intrinsic attenuation as sound energy passes through materials due to conversion of energy into heat which is quickly dissipated; this is the cause of energy losses discussed by Hamilton (1972).

2. Transmission through reflectors (including multiple reflections, "peg-leg multiples"): These reflection and refraction losses (and reinforcements) also include conversion of compressional to shear waves and consequent rapid attenuation.

3. Reflector roughness and curvature: Focussing and defocussing effects of concave and convex reflectors (easily seen on any echo sounder or acoustic reflection record).

4. Scattering by inhomogeneities: Found within the sediment or rock body or along reflector surfaces.

Thus, when low-frequency sound of sufficient energy enters the sea floor, it loses energy through many causes, only one of which is intrinsic attenuation in the various materials. The total of all losses (excluding spreading losses) is called effective attenuation.

(U) The little data available for determining compressional wave effective attenuation as a function of depth in the sea floor have been collected and interpreted by Hamilton (1976a). Figure 17 is reproduced from this report. It appears from this study and later work by Tyce (unpublished) that there is little difference in sediment surface values of intrinsic attenuation and effective attenuation in the first few tens of meters in the sea floor.

(U) Recent measurements of compressional wave effective attenuation in sediment wedges at 4 kHz have been made by Tyce (unpublished) in various seafloor environments using the Marine Physical Laboratory (University of California) Deeptow instrument package. Porosities and mean grain sizes in sediments cored in some of these areas, when entered in the k_p as a function of porosity and mean-grain-size diagrams, yielded reasonably close predictions of the actual attenuation measurements, although Tyce's measurements must be considered as effective attenuation (as discussed above). An overall conclusion from Tyce's data is that his measurements favored the lower part of the range of values for k_p, which might have been predicted from Hamilton (1972) for higher porosity sediments (0.05 to 0.20), i.e., his overall range was 0.03 to 0.16. Without the one value of 0.16, the range was 0.03 to 0.10.

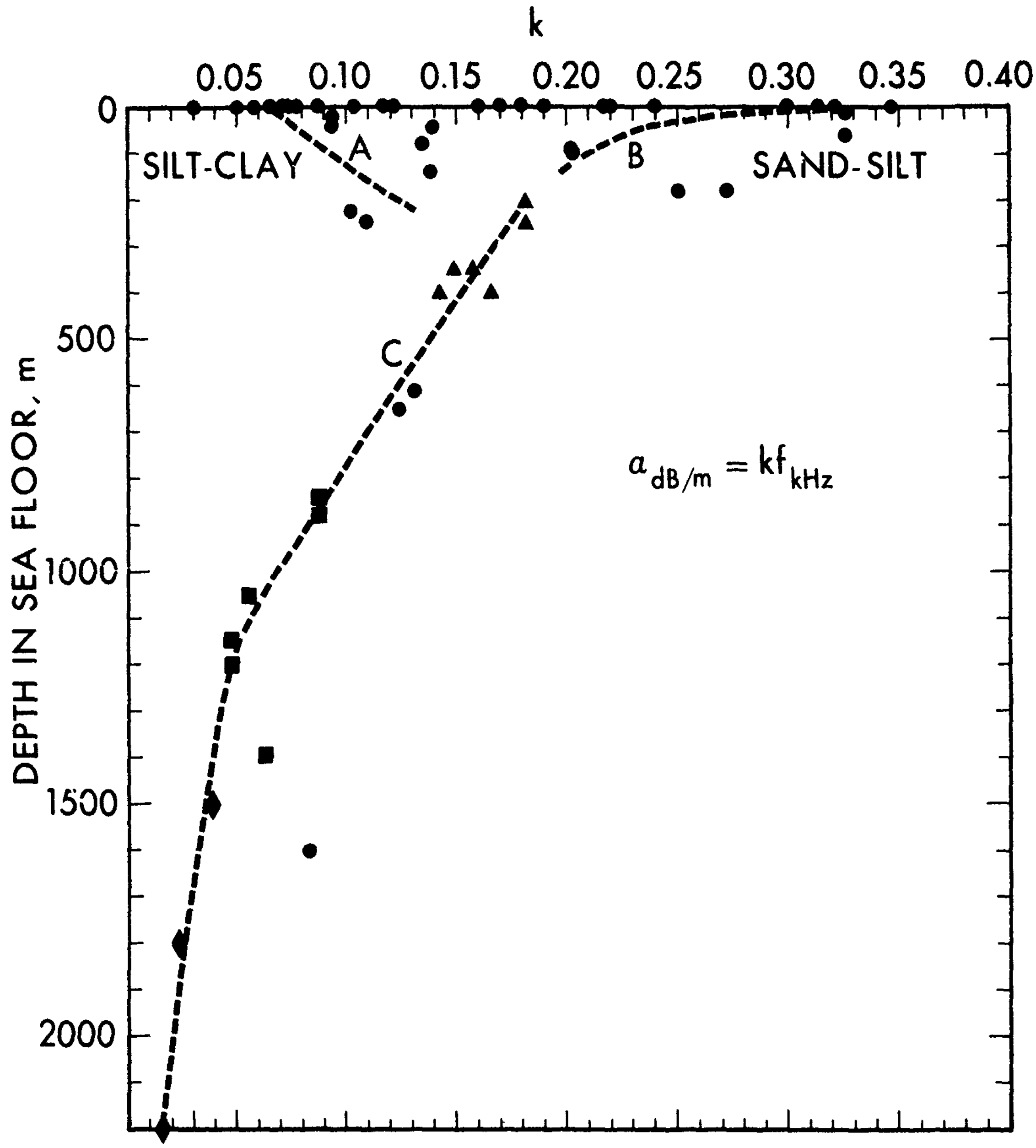

Figure 17. (U) Attenuation of compressional waves (expressed as the constant k in attenuation in dB/m, $\alpha_p = kf_{kHz}$) as a function of depth in the sea floor (Hamilton, 1976a). The closed circles represent measurements from the literature; the triangles, squares, and diamonds represent the first, second, and third layers, respectively, in the sea floor in seven areas (from Neprochnov, 1971). See Hamilton (1976a) for additional information. (U)

(U) Almost all information on effective attenuation as a function of depth in the sea floor is from Soviet sources, which were summarized by Neprochnov (1971). Values of recommended attenuation in the models at and below depths of 400 m are from this source (see Hamilton, 1976a, for data and discussion). Neprochnov listed an attenuation which was converted into a value of 0.14 for k_p at a depth of 400 m (interval of 0 to about 800 m) in the first sediment layer in the Arabian Sea. This value was accepted at 400 m for all models.

(U) In summary, the values of k_p in the models were derived as follows:

1. The recommended sediment surface value of k_p was predicted from relationships for porosity as a function of k_p.

2. A line was drawn between this recommended surface value and the value of 0.14 at 400 m using the diagram published by Hamilton (1976a, reproduced here as figure 17). Values of k_p were taken off this line at 100-m depth intervals. This same method was used to determine maximum and minimum values between 0 and 400 m. For example (geoacoustic model 4a, Somali Basin):

Depth, m	k_p		
	Minimum	Recommended	Maximum
Sfc	0.04	0.07	0.18
100	0.06	0.09	0.17
200	0.09	0.11	0.16
300	0.11	0.12	0.15
400	–	0.14	–

3. From depths of 400 to about 2000 m in the sediments, the k_p values were taken at 100-m depth intervals along line C of figure 17; they are the same in all models. At 2000 m, the value of k_p is about 0.02. At depths greater than 2000 m in the sedimentary rocks, a value of 0.02 was used.

4. For basalt a value of 0.03 was used for k_p (Hamilton, 1976a), except when the sedimentary rock above the basalt was 0.02. In this case, a value of 0.02 was also used for the basalt.

Attenuation of Shear Waves (U)

(U) Hamilton (1976c) recently summarized and reviewed the sparse data available on the attenuation of shear waves in marine sediments. In this report, attenuation of shear waves (α_s) in decibels per meter was related to frequency (f) in kilohertz through a constant (k_s) in the equation

$$\alpha_s = k_s f \quad (19)$$

(U) The values of k_s at the sediment surface or in lower rock layers in the geoacoustic models were selected from the data in Hamilton (1976c). These values (plus that for basalt) are as follows:

Sediment or Rock Type	k_s
Silt-clays	15
Sand-silt	13
Mudstone	10
Shale	3
Basalt	0.07 (Levykin, 1965)

(U) Very little information is available on the variations of shear wave attenuation with pressure or with depth in sediments and rocks. Gardner et al. (1964) found that in unconsolidated (uncemented) sands attenuation of shear and compressional waves varied about the same under increasing, normal, effective pressures, i.e., attenuation decreased with about the 1/6 power of overburden pressure. Levykin (1965) showed that both compressional wave and shear wave attenuation decreased about the same in low-porosity rocks under increasing effective pressure. There are no data on the effects of pressure on shear wave attenuation in unlithified, higher porosity silt-clays.

(U) In the absence of data and in view of the work of Gardner et al. and Levykin, it was assumed for this report that shear wave attenuation varied with depth in the sea floor proportionally with compressional wave attenuation. Those values of k_s shown at various depths in the first thick layer in the geoacoustic models were derived from a simple proportion starting at the sediment surface: k_s at Sfc/k_p at Sfc = k_s at depth/k_p at depth. The values of k_s in the lower rock layers were determined from the table above.

Density (U)

(U) The saturated bulk density at the surface of the sea floor (ρ_{sat}) in grams per cubic centimeter was computed from the area's generalized, averaged coring data using sediment fractional porosity (n), bottom-water density (ρ_w), and bulk mineral grain density (ρ_s) in the equation

$$\rho_{sat} = n\rho_w + (1 - n)\,\rho_s \quad .^* \tag{20}$$

(U) Two recent reports discussed variations of density with depth in sea-floor sediments and rocks. The first report (Hamilton, 1976b) was concerned with density as a function of depth in soft sediments in the sea floor. Based mainly on DSDP samples, e.g., Bachman and Hamilton (1976), in situ profiles of porosity and density as a function of depth were constructed for some important sediment types: calcareous and siliceous oozes, pelagic clay, and terrigenous sediments. The diagram and equations involving terrigenous and calcareous sediments were used for several thin, soft layers in the geoacoustic models in this report. However, most data on density with depth in the thick first sediment and sedimentary rock layers were based on the second report (Hamilton, 1978).

(U) Measurements of denisty and velocity in marine sediments and rocks were combined with information from the literature, and a report was published (Hamilton, 1978) which related density with velocity for common sediments and rocks. (Figure 18 is

*(U) To convert g/cm^3 to kg/m^3 (SI units), multiply by 1000.

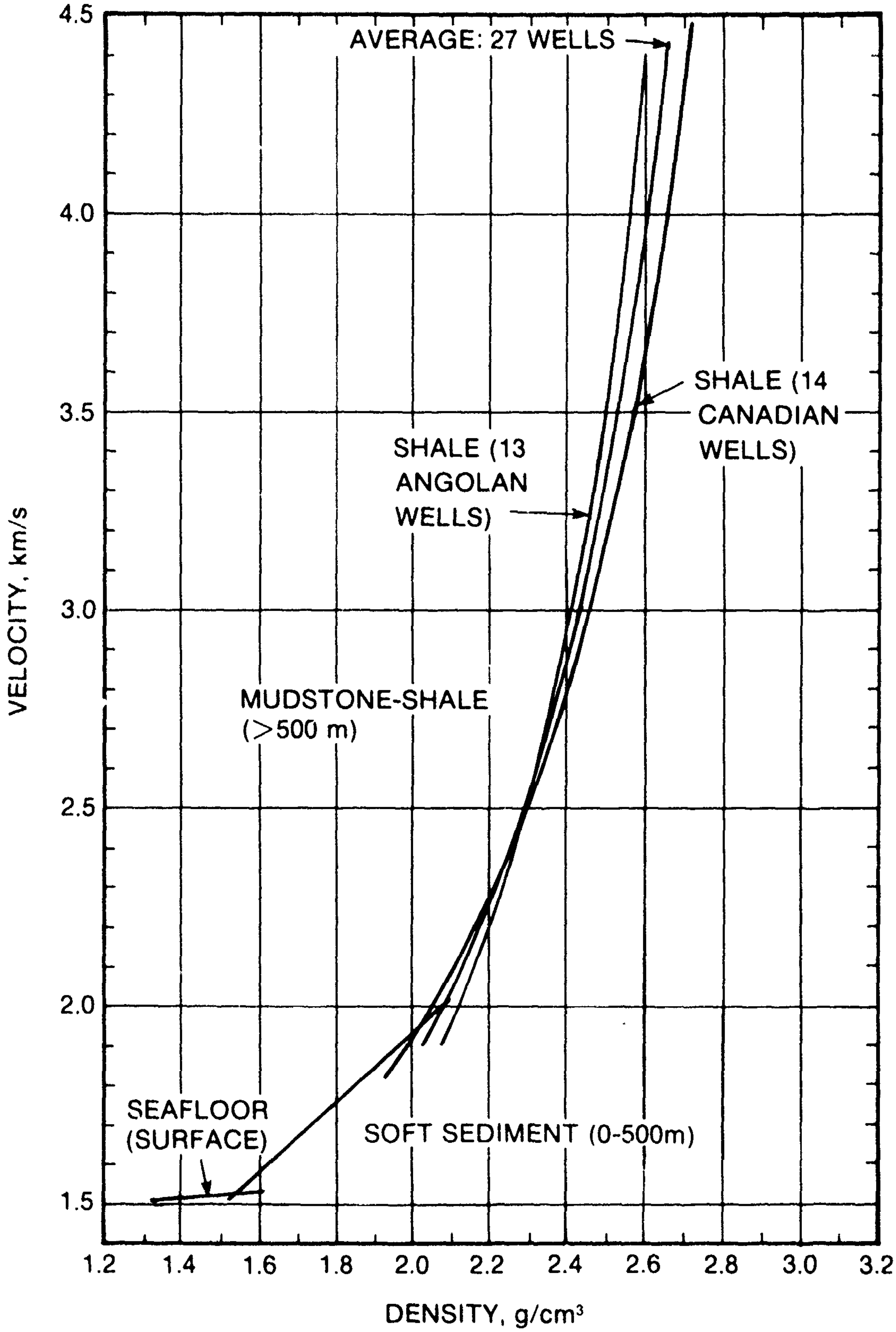

Figure 18. (U) Compressional wave velocity as a function of density in marine sediments (silt-clays, turbidites) and sedimentary rocks (mudstones, shales). See text, this report, and Hamilton (1978) for additional information. (U)

reproduced from figure 1 of the 1978 report.) Figure 18 shows curves relating sound velocity to density in silt-clays, turbidites, and sedimentary rocks (mudstones and shales). This allows the use of velocity determined from reflection and refraction surveys to be used as an index to derive a reasonable estimate of density. The values of velocity used to estimate density at depth were derived as discussed in the section "Compressional Wave (Sound) Velocity." These values are listed in each model under the heading V_p. The equations for portions of the illustrated curves (figure 18) are

from V_p = 1.53 to 2.00 km/s

$$\rho_{sat} = 1.135V_p - 0.190 \tag{21}$$

for V_p greater than 2.00 km/s

$$\rho_{sat} = 0.917 + 0.744\,V_p - 0.08V_p^2 \ . \tag{22}$$

(U) The values of density shown in the models for basalts were derived from Christensen and Salisbury (1975). (Their data were reproduced in Hamilton (1978) and in this report as figure 14.)

Sediment and Rock Types (U)

(U) The sediment and rock types shown in the main tables and footnotes for each model in Appendices A and B were based on cores from the expedition, information from the literature (especially that from the sites of the Deep Sea Drilling Project), interpretation of reflection, refraction, and sonobuoy records, and geological probabilities.

PART III. EXTRAPOLATED GEOACOUSTIC MODELS (U)

INTRODUCTION (U)

(C) Part II was concerned with geoacoustic models of the sea floor in the northwestern Indian Ocean along ship's tracks where bottom-loss measurements were made during BEARING STAKE. This part (III) presents nine additional models (Appendix B) which extrapolate the geophysical and geological data within adjacent geomorphic provinces. All models in both parts should be used in extrapolating data and models.

(U) All the extrapolated models are generalized and approximate. They are intended as estimates to allow a rationale for an acoustician to extrapolate or predict bottom losses or reflection coefficients in these general areas. The methods used to derive the values listed in the tables are discussed in Part II.

(U) The three general areas discussed in Part III are distinctive geomorphic provinces: Oman Basin, Arabian Fan and adjacent areas in the Arabian Basin, and Somali Basin. The geology of these areas was discussed in Part II, and the bathymetry was illustrated in figure 1. Examples of acoustic reflection records are in figures 2 through 6.

OMAN BASIN (U)

(U) The Oman Basin (figures 1 and 2) is formed by a very flat abyssal plain surrounded by hills to the north and northwest, by the continental terrace to the east, by Murray Ridge to the southeast, and by the Arabian Penisula to the southwest.

(U) In the Oman Basin, geoacoustic model 1a (Appendix A) can be extrapolated within the flat, abyssal plain in the center of the basin. It is recommended that this model be used within, i.e., deeper than, the 3000-m, water-depth contour.

(U) Geoacoustic model 1b (Appendix A) is intended for use in the folded sedimentary ridges of the continental slope northeast, north, and northwest of the abyssal plain in the Gulf of Oman. These ridges are probably formed by squeezing and compressing former abyssal plain sediments with a thin layer of pelagic sediments on their tops. This model represents the ridge tops. The upper layer is based on coring data, but the lower layers are tenuous assumptions.

ARABIAN FAN (U)

(C) Geoacoustic models 3a, 3b, and 3c (figure 1, Appendix A) were along a line in the north-central fan where bottom-loss measurements were made during BEARING STAKE. Additional models, A1 through A5, were made to allow extrapolation of data to most of the remainder of the fan. Model 2b (Appendix A) is along an expedition line in area 2, but no bottom-loss measurements are currently available along this line. Model 2b can be used as an additional model for extrapolation.

(C) The additional models (A1 through A5) were placed to provide reasonable area coverage over the fan and where additional information was available on sediment and sedimentary rock thicknesses. These models were placed as follows (see figure 1 and the latitude and longitude in appropriate tables in Appendix B):

1. (C) Geoacoustic model A1 was placed in the southeast fan near an acoustic reflection line between Deep Sea Drilling Project sites 221 and 222.

2. (C) Geoacoustic model A2 was along a USNS WILKES acoustic reflection line in the south-central fan

3. (C) Geoacoustic model A3a in the south-central fan was placed on a WILKES track. Models A3b and A3c were placed in the southeast and southwest fan on the 1000-m, sediment-thickness (isopach) line of Naini and Talwani (personal communication, 1977).

4. (C) Geoacoustic models A4a and A4b were near the southern end of the fan and on the 500-m, sediment-thickness contour line of Naini and Talwani.

5. (C) Geoacoustic model A5 was placed to obtain area coverage in the northwest fan. It is on the 3400-m, water-depth contour. The sediment thickness from Naini and Talwani is 2300 m.

(U) All models for the Arabian Fan are essentially the same, except for the Sfc properties which depend on water depth. This is because a common velocity-sediment depth curve was averaged from sonobuoy measurements and used over the entire fan and because generalized data for the upper 3 m of sediments were determined from averages in eight cores in area 3 and used for the entire fan.

Owen Ridge (U)

(U) Owen Ridge forms the western boundary of the Arabian Fan (figure 1). It is an uplifted block of sediments and rocks which is tilted to form a low slope to the west. The eastern boundary of Owen Ridge is a relatively steep fault scarp.

(C) Geoacoustic model 2a (Appendix A) is on top of Owen Ridge in BEARING STAKE area 2. DSDP site 224 was drilled to the north of model 2a (as 16°33'N, 59°42'E), and the DSDP report furnished much of the data used to formulate the model.

(U) Although on top of a ridge, there is a thick section for this environment (795 m of sediments and sedimentary rocks over basalt). There are no models farther west, but model 2a can be used to compute bottom losses into the basin to the west, for example, along KINGSPORT track 2P1 (figure 1). For some acoustic modeling purposes, special attention should be accorded the asymmetric nature of Owen Ridge. The fault scarp on the east side of the ridge (in the vicinity of area 2) has a slope of about 17°. On the west side of the ridge, the relatively low slope is about 2.5°.

Carlsberg Ridge (U)

(U) Carlsberg Ridge which forms the southern boundary of the Arabian Fan was described in the section "Geologic Setting." This basaltic ridge, as noted, is rough with steep escarpments, gaps, fissures, isolated ridges, and seamounts. Near and along the tops of this feature, there are only thin patches of sediments in depressions.

(U) As rugged topography controls bottom losses, it is impossible to model the area as a generality. Small areas could be modeled given a very detailed bathymetric chart. Geoacoustic model A6, placed on the crest of the Carlsberg Ridge, indicates a small area where basaltic lavas are at the sea floor with no sediment cover. The velocity data are from a seismic refraction survey line measured by the Soviets through 5°00'N, 62°30'E.

SOMALI BASIN (U)

(U) Geoacoustic models 4a, 4b, and 4c (Appendix A) can be used to extrapolate data in the Somali Basin and adjacent areas. Model 4a, in the center of the plain, can be used within the 4800-m contour (figure 1). Model 4b can be used for the slopes and top of Chain Ridge on the east side of the basin. Geoacoustic model 4c can be used to represent the African continental rise, west of the basin, from the 4800-m contour to about the 4000-m contour.

APPENDIX A. BEARING STAKE GEOACOUSTIC MODELS (U)

INTRODUCTION (U)

(C) The following ten geoacoustic models of the sea floor are along the tracks of the USNS KINGSPORT during BEARING STAKE. They are primarily intended for use in reconciling experimental bottom-loss measurements with theory and secondarily for use with the other models in Part III for extrapolating measurements and predictions to other adjacent areas.

(U) The geologic setting of the geoacoustic models and the methods used to derive the values in the tables were discussed in Part II.

(U) In the following tables, values are usually not rounded off, but are shown as computed (to indicate trends and gradients). There is no intent to indicate accuracy or probable errors. All values must be considered as generalizations and estimates, especially when one model is extrapolated over a general area or along an insonified line along the sea floor.

GEOACOUSTIC MODEL 1a (U)

(C) **Geoacoustic model**: 1a   **Area**: Gulf of Oman (areas 1A and 1B)

Location: 23°33′N latitude; 61°09′E longitude

Water depth: Echo sounder: 1826 fathoms; 3340 m; set at 1500 m/s
Corrected: 1831 fathoms; 3348 m (from station data)

Province and description of the sea floor: Abyssal Plain Province. The sea floor is composed of a first layer of flat-lying turbidites overlying two other sedimentary rock layers which dip to the north. The acoustic basement is probably basalt.

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity, m/s V_p(3)	Velocity, m/s V_s(4)	Attenuation, k_p(5)	Attenuation, k_s(6)	Density, g/cm^3(7)
Bottom Water				1514.5				1.04306
Sea Floor								
1			Sfc(8)	1515	120	0.05-0.10-0.20	15.0	1.58
			100	1638	377	0.07-0.11-0.19	16.5	1.67
			200	1750	442	0.10-0.12-0.17	18.0	1.80
			300	1851	499	0.12-0.13-0.16	19.5	1.91
			400	1943	558	0.14	21.0	2.02
			500	2026	619	0.14	21.0	2.10
			600	2101	679	0.12	18.0	2.13
Sediment and Sedimentary Rock	0.62	1250	700	2168	730	0.11	16.5	2.15
			800	2230	780	0.10	15.0	2.18
			900	2286	820	0.08	12.0	2.20
			1000	2337	860	0.07	10.5	2.22
			1100	2385	900	0.06	9.0	2.24
			1200	2429	935	0.05	7.5	2.25
			1250-	2450	950	0.05	7.5	2.26
2			1250+	2565	1040	0.05	7.5	2.30
Sedimentary Rock	0.34	986 (493)	1743	2900	1300	0.03	4.5	2.40
			2236-	3235	1560	0.02	3.0	2.49
3			2236+	3400	1700	0.02	3.0	2.52
Sedimentary Rock	0.30	1104 (552)	2788	3685	1843	0.02	3.0	2.57
			3340-	3975	1988	0.02	3.0	2.61
4 Basalt			3340+	4600	2270	0.02	0.07	2.50

(U) Notes (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):
   a. First layer:

   $$V_p = 1.515 + 1.292D - 0.611D^2 + 0.141D^3,$$

   where V_p is in km/s and depth in the sea floor (D) is in km.

   b. Lower layers: V_ps from literature.
4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).
5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum value, recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).
6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface; proportional to k_p at depth.
7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978, 1976b). Basalt density from Christensen and Salisbury (1975).
8. Sfc values are a composite for the 0- to 1-m depth interval. For a detailed model of this interval see the diagram and the following data.

(U) Detail of First Meter (U)

Layer Material	Thickness, s	Thickness, m	Depth, m	Velocity, m/s V_p	Velocity, m/s V_s	Attenuation, k_p	Attenuation, k_s	Density, g/cm^3
Bottom Water				1514.5				1.04306
Sea Floor								
			Sfc	1485	115	0.05-0.10-0.20	1.50	1.53
1a Silt-clay		0.8						
			0.8-	1486	119	0.05-0.10-0.20	15.0	1.53
			0.8+					
1b Silt		0.2		1620	130	0.45-0.60-0.85	13.0	1.80
			1.0-					

(U) Notes

1. The geoacoustic models (such as in the main table) showing thick sediment and sedimentary rock sections over acoustic basement, e.g., basalt, are generalized and do not account for the multiple reflectors usually seen at high frequencies, e.g., in the 3.5-kHz records or in cores.

2. If a detailed, multireflector model is desired, the above sequence of a thicker silt-clay layer and a thinner silt (or other) layer can be alternated to any desired depth. If so, the property values can be corrected for depth as follows:

   a. For the silt-clay layer:

      (1) For V_p: increase V_p using gradients computed from the equation for V_p as a function of depth.

      (2) Other properties: vary the value of the property with depth using the appropriate gradient from the values listed in the main table.

   b. For the silt (or other layer):

      (1) For V_p: increase V_p as above for silt-clay.

      (2) For k_p: vary k_p along lines b and c (figure 17).

      (3) Other properties: as above for silt clay.

3. It should be noted that in areas where turbidites form abyssal plains or fans (such as in the Oman Basin, Arabian Fan, and Somali Basin) the reflectors usually represent coarser sediments spilling discontinuously from leveed channels. These reflectors cannot usually be followed over very great distances or correlated from area to area. Any detail, as above, is a gross generalization of widely varying layers (in thickness and properties).

4. The values listed in the main table for Sfc are composite proportional values for the first 1 m of sediment. Other properties in three cores for the 0- to 1-m depth are as follows (silt-clay porosity was salt-corrected from core 4 in center of basin; silt porosity from velocity-porosity relations of other data):

Property	Silt-clay	Silt
Velocity ratio	0.98	1.07
	composite: 1.00	
Porosity, %	71	55
	composite: 68	
Mean grain size, ϕ	8.39	6.09
(number in sample)	(46)	(6)
Grain density, g/cm^3	Average of all samples: 2.73	
(number in sample)		(56)

5. Although these generalized data indicate a sharp top boundary between the silt-clay and silt layers, it is more apt to be gradational in all properties.

(U) In Situ Properties of Bottom Water (U)

True Depth, m	T, °C	S, ppt	P, kg/cm^2	Sound Speed, m/sec	Density, g/cm^3	Impedance, g/cm^2 sec X 10^5
3348	1.83	34.74	346.7	1514.5	1.04306	1.57971

GEOACOUSTIC MODEL 1b (U)

(C) <u>Geoacoustic model:</u> 1b <u>Area:</u> Gulf of Oman (areas 1A and 1B)

<u>Location:</u> 24°27′N latitude, 58°33′E longitude

<u>Water depth:</u> Echo sounder: 1323 fathoms; 2420 m; set at 1500 m/s
Corrected: 1327 fathoms; 2427 m (from station data)

<u>Province and description of the sea floor:</u> Ridges on Continental Slope. The continental slope northeast, north, and northwest of the Gulf of Oman's abyssal plain is composed of east-west trending ridges which were formed by squeezing and compressing former abyssal-plain sediments to the south. Geoacoustic model 1b represents the ridge tops.

Layer Material	Thickness, s(1)	Thickness, m(2)		Depth, m	Velocity, m/s V_p(3)	Velocity, m/s V_s(4)	Attenuation, k_p(5)	Attenuation, k_s(6)	Density, g/cm^3(7)
Bottom Water					1499.6				1.03895
Sea Floor									
1				Sfc(8)	1470	113	0.04–0.08–0.19	15	1.46
Sediment	0.035	55	28	28	1505	165	0.04–0.09–0.19	17	1.50
				55−	1540	217	0.05–0.09–0.18	17	1.53
2				55+	2000	600	0.14	26	2.08
Sedimentary Rock	0.10	206	103	158	2065	650	0.13	24	2.11
				260−	2130	705	0.11	21	2.14
3 Sedimentary Rock				260+	3000	1375	0.03	4.5	2.43

(U) <u>Notes</u> (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):

   a. First layer:

   $$V_p = 1.47 + 1.28D,$$

   where V_p is in km/s and depth in the sea floor (D) is in km.

   b. Lower layers: V_ps from literature.
4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks.
5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum value, recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976).

6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface; proportional to k_p at depth.

7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978, 1976b).

8. Other averaged sediment properties for the surface (Sfc), 0 to 30 cm, for core 2 at the location of the model:

Velocity ratio	0.98
Porosity, %	75
Mean grain size, ϕ	8.84
Grain density, g/cm^3	2.72
Sediment type	Silty clay and clay

(U) In Situ Properties of Bottom Water (U)*

True Depth, m	T, °C	S, ppt	P, kg/cm^2	Sound Speed, m/sec	Density, g/cm^3	Impedance, g/cm^2 sec × 10^5
2427	2.20	34.78	251.1	1499.6	1.03895	1.55801

*At location of model: core 2

GEOACOUSTIC MODEL 2a (U)

(C) **Geoacoustic model:** 2a   **Area:** Owen Ridge

Location: 16°15′N latitude; 59°46′E longitude

Water depth: Echo sounder. 1099 fathoms; 2010 m; set at 1500 m/s
Corrected: 1102 fathoms; 2015 m (Matthews' Tables)

Province and description of the sea floor: Ridge and seamount province. This model can be used along the top and west side of Owen Ridge which lies along the west side of the Arabian Fan. The east side of the ridge is a fault scarp.

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity, m/s $V_p(3)$	Velocity, m/s $V_s(4)$	Attenuation, $k_p(5)$	Attenuation, $k_s(6)$	Density, $g/cm^3(7)$
Bottom Water				1496.8				1.03701
Sea Floor								
1 Sediment	0.065	100	Sfc(8)	1480	115	0.05-0.09-0.20	15.0	1.50
			100-	1605	340	0.07-0.10-0.19	16.7	1.63
2 Claystone, Siltstone	0.095	175	100+	1800	470	0.09	10.0	1.95
			275-	1900	530	0.09	10.0	2.05
3 Chalk, Claystone	0.220	520	275+	2100	1105	0.08	3.0	2.10
			795-	2685	1415	0.08	3.0	2.28
4 Basalt			795+	4600	2275	0.03	0.07	2.51

(U) **Notes** (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):
   a. First layer:

      $V_p = 1.48 + 1.24D,$

      where V_p is in km/s and depth in the sea floor (D) is in km.

   b. Lower layers: V_ps from literature.
4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).
5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum value, recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).

6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface; proportional to k_p at depth.

7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978, 1976b). Basalt density from Christensen and Salisbury (1975).

8. Other averaged sediment surface (Sfc) properties (0 to 1 m) in core 13 at the location of the model:

Velocity ratio	0.99
Porosity, %	72
Mean grain size, ϕ	6.23
Grain density, g/cm^3	2.69
Sediment type	Mostly calcareous sand-silt-clay

(U) <u>In Situ</u> Properties of Bottom Water (U)*

True Depth, m	T, °C	S, ppt	P, kg/cm^2	Sound Speed, m/sec	Density, g/cm^3	Impedance, g/cm^2 sec × 10^5
2015	3.27	34.86	208.4	1496.8	1.03701	1.55220

*At location of model: core 13

GEOACOUSTIC MODEL 2b (U)

(C) **Geoacoustic model:** 2b **Area:** Arabian Fan, West Central

Location: 15°57'N latitude; 61°55'E longitude

Water deptn. Echo sounder: 2154 fathoms; 3939 m; set at 1500 m/s
Corrected: 2163 fathoms; 3956 m (Matthews' Tables)

Province and description of the sea floor: Abyssal plain (abyssal deep sea fan) province. The Arabian Fan (or Cone) was formed by very thick accumulations of turbidity current deposits overlying basalt. The sediments are transported through natural, leveed channels from sources in northern India and Pakistan and deposited on the fan.

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity, m/s V_p(3)	Velocity, m/s V_s(4)	Attenuation, k_p(5)	Attenuation, k_s(6)	Density, g/cm^3(7)
Bottom Water				1524.7				1.04574
Sea Floor								
1			Sfc(8)	1509	125	0.05-0.10-0.20	15.0	1.57
			100	1627	365	0.07-0.11-0.19	16.5	1.66
			200	1739	437	0.10-0.12-0.17	18.0	1.78
			300	1847	496	0.12-0.13-0.16	19.5	1.91
			400	1951	564	0.14	21.0	2.02
			500	2050	637	0.14	21.0	2.11
Sediment			600	2145	717	0.12	18.0	2.14
and	1.09	2750	700	2237	783	0.11	16.5	2.18
Sedimentary			800	2324	851	0.10	15.0	2.21
Rock			900	2409	917	0.08	12.0	2.25
			1000	2490	980	0.07	10.5	2.27
			1500	2855	1265	0.04	6.0	2.39
			2000	3169	1510	0.02	3.0	2.47
			2500	3459	1730	0.02	3.0	2.53
			2750-	3600	1800	0.02	3.0	2.56
2								
Basalt			2750+	5400	2744	0.02	0.07	2.72

(U) **Notes** (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):

   a. First layer:

   $$V_p = 1.509 + 1.20D - 0.253D^2 + 0.034D^3,$$

   where V_p is in km/s and depth in the sea floor (D) is in km.

   b. Lower layers: V_ps from literature.

4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).

5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum value, recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).

6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface; proportional to k_p at depth.

7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978, 1976b). Basalt density from Christensen and Salisbury (1975).

8. In the above model, the Sfc values are a composite of the 0- to 3-m interval. If a detailed model of this depth interval is desired, use the detailed model from model 3a and change silt-clay V_ps to 1494 (Sfc, V_p ratio of 0.98) and 1497 at 2.8 m.

(U) In Situ Properties of Bottom Water (U)

True Depth, m	T, °C	S, ppt	P, kg/cm^2	Sound Speed, m/sec	Density, g/cm^3	Impedance, g/cm^2 sec × 10^5
3956	1.73	34.73	410.1	1524.7	1.04574	1.59444

GEOACOUSTIC MODEL 3a (U)

(C) **Geoacoustic model:** 3a* **Area:** Arabian Sea, Central Arabian Fan

Location: 15°44′N latitude; 64°32′E longitude

Water depth. Echo sounder: 2081 fathoms; 3805 m; set at 1500 m/s
Corrected: 2089 fathoms; 3820 m (Matthews' Tables)

Province and description of the sea floor: Abyssal plain (abyssal deep sea fan) province. The Arabian Fan (or Cone) was formed by very thick accumulations of turbidity current deposits overlying basalt. The sediments are transported through natural, leveed channels from sources in northern India and Pakistan and deposited on the fan.

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity. m/s V_p(3)	Velocity. m/s V_s(4)	Attenuation, k_p(5)	Attenuation, k_s(6)	Density, g/cm^3(7)
Bottom Water				1521.5				1.04514
Sea Floor								
1			Sfc(8)	1506	125	0.05-0.10-0.20	15.0	1.57
			100	1624	361	0.07-0.11-0.19	16.5	1.65
			200	1736	435	0.10-0.12-0.17	18.0	1.78
			300	1844	494	0.12-0.13-0.16	19.5	1.90
			400	1948	562	0.14	21.0	2.02
			500	2047	635	0.14	21.0	2.10
			600	2142	714	0.12	18.0	2.14
			700	2234	780	0.11	16.5	2.17
Sediment and Sedimentary Rock	1.30	3540	800	2321	850	0.10	15.0	2.21
			900	2406	915	0.08	12.0	2.24
			1000	2487	975	0.07	10.5	2.27
			1500	2852	1260	0.04	6.0	2.38
			2000	3166	1503	0.02	3.0	2.47
			2500	3456	1728	0.02	3.0	2.53
			3000	3747	1874	0.02	3.0	2.58
			3500	4065	2033	0.02	3.0	2.62
			3530-	4085	2043	0.02	3.0	2.62
2 Basalt			3530+	5400	2744	0.02	0.07	2.72

(U) **Notes** (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):

   a. First layer:

   $$V_p = 1.506 + 1.20D - 0.253D^2 + 0.034D^3,$$

   where V_p is in km/s and depth in the sea floor (D) is in km.

*The relationships between geoacoustic model 3a and the other models in area 3 (3b, 3c) are indicated in figure 3.

b. Lower layers: V_ps from literature.

4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).

5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum value, recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).

6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface, proportional to k_p at depth.

7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978, 1976b). Basalt density from Christensen and Salisbury (1975).

8. In the above model, the Sfc values are a composite of the 0- to 3-m depth interval. For a detailed model of this interval see the diagram and notes below.

(U) Detail of First 3 Meters (U)

Layer Material	Thickness, s	Thickness, m	Depth, m	Velocity, m/s V_p	Velocity, m/s V_s	Attenuation, k_p	Attenuation, k_s	Density, g/cm^3
Bottom Water				1521.5				1.04514
Sea Floor								
			Sfc	1491	115	0.05-0.10-0.20	15.0	1.55
1a Silt-clay		2.8						
			2.8-	1494	128	0.05-0.10-0.20	15.0	1.55
			2.8+					
1b Sand-silt-clay		0.2		1610	175	0.45-0.60-0.85	13.0	1.80
			3.0-					

(U) Notes

1. The geoacoustic models (such as in the main table) showing thick sediment and sedimentary rock sections over acoustic basement, e.g., basalt, are generalized and do not account for the multiple reflectors usually seen at high frequencies, e.g., in the 3.5-kHz records or in cores.

2. If a detailed, multireflector model is desired, the above sequence of a thicker silt-clay layer and a thinner silt (or other) layer can be alternated to any desired depth. If so, the property values can be corrected for depth as follows:

   a. For the silt-clay layer:

      (1) For V_p, increase V_p using gradients computed from the equation for V_p as a function of depth.

(2) Other properties: vary the value of the property with depth using the appropriate gradient from the values listed in the main table.

b. For the silt (or other layer):

(1) For V_p: increase V_p as above for silt-clay.

(2) For k_p: vary along lines b and c (figure 17).

(3) Other properties: as above for silt clay.

3. It should be noted that in areas where turbidites form abyssal plains or fans (such as in the Oman Basin, Arabian Fan, and Somali Basin), the reflectors usually represent coarser sediments spilling discontinuously from leveed channels. These reflectors cannot usually be followed over very great distances or correlated from area to area. Any detail, as above, is a gross generalization of widely varying layers (in thickness and properties).

4. The values listed in the main table for Sfc are composite values for the depth interval of 0 to 3 m (illustrated above). Some averaged properties in eight cores for this interval, other than those listed above, are as follows (silt-clay porosity is based on salt-corrected value in first two samples in each core; sand-silt-clay porosity based on velocity-porosity relations from other data):

Property	Silt-clay	Sand-silt-clay
Velocity ratio	0.98	1.06
	composite: 0.99	
Porosity, %	70	55
	composite: 69	
Mean grain size, ϕ	8.55	6.86
(number in sample)	(466)	(2)
Grain density, g/cm^3	Average of all samples: 2.74	
(number in sample)		(457)

5. Although these generalized data indicate a sharp top boundary between the silt-clay and sand-silt-clay layers, it is more apt to be gradational in all properties.

(U) In Situ Properties of Bottom Water (U)

True Depth, m	T, °C	S, ppt	P kg/cm^2	Sound Speed, m/sec	Density, g/cm^3	Impedance, g/cm^2 sec X 10^5
3820	1.73	34.72	395.9	1521.5	1.04514	1.59018

GEOACOUSTIC MODEL 3b (U)

(C) Geoacoustic model: 3b* Area: Arabian Sea, Central Arabian Fan

Location: 17°19′N latitude; 65°25′E longitude

Water depth: Echo sounder: 1908 fathoms; 3489 m; set at 1500 m/s
Corrected: 1914 fathoms; 3500 m (Matthews' Tables)

Province and description of the sea floor: Abyssal plain (abyssal deep sea fan) province. The Arabian Fan (or Cone) was formed by very thick accumulations of turbidity current deposits overlying basalt. The sediments are transported through natural, leveed channels from sources in northern India and Pakistan and deposited on the fan.

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity, m/s V_p(3)	Velocity, m/s V_s(4)	Attenuation, k_p(5)	Attenuation, k_s(6)	Density, g/cm^3(7)
Bottom Water				1516.5				1.04373
Sea Floor								
1			Sfc(8)	1501	125	0.05-0.10-0.20	15.0	1.57
			100	1619	356	0.07-0.11-0.19	16.5	1.65
			200	1731	433	0.10-0.12-0.17	18.0	1.77
			300	1839	491	0.12-0.13-0.16	19.5	1.90
			400	1943	558	0.14	21.0	2.02
			500	2042	631	0.14	21.0	2.10
Sediment and Sedimentary Rock	1.23	3260	600	2137	710	0.12	18.0	2.14
			700	2229	780	0.11	16.5	2.17
			800	2316	845	0.10	15.0	2.21
			900	2401	910	0.08	12.0	2.24
			1000	2482	975	0.07	10.5	2.27
			1500	2847	1255	0.04	6.0	2.38
			2000	3161	1500	0.02	3.0	2.47
			2500	3451	1726	0.02	3.0	2.53
			3000	3742	1871	0.02	3.0	2.58
			3260-	3902	1951	0.02	3.0	2.60
2 Basalt			3260+	5400	2744	0.02	0.07	2.72

(U) Notes (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):

   a. First layer:

   $$V_p = 1.501 + 1.20D - 0.253D^2 + 0.034D^3,$$

   where V_p is in km/s and depth in the sea floor (D) is in km.

*The relationships between geoacoustic model 3b and the other models in area 3 (3a, 3c) are indicated in figure 3.

b. Lower layers: V_ps from literature.

4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).

5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum valu. recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).

6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface; proportional to k_p at depth.

7. Density (saturated bulk density in situ). Surface densit .nputed from core data. Density at depth from Hamilton (1978, 1976b). Basalt density from Christensen and Salisbury (1975).

8. In the above model, the Sfc values are a composite of the 0- to 3-m depth interval. If a detailed model of this interval is desired, use the detailed model in 3a and change silt-clay V_ps to 1486 (Sfc, V_p ratio of 0.98) and 1489 at 2.8 m.

(U) <u>In Situ</u> Properties of Bottom Water (U)

True Depth, m	T, °C	S, ppt	P, kg/cm^2	Sound Speed, m/sec	Density, g/cm^3	Impedance, g/cm^2 sec $\times 10^5$
3500	1.74	34.73	362.5	1516.5	1.04373	1.58282

GEOACOUSTIC MODEL 3c (U)

(C) Geoacoustic model: 3c* Area: Arabian Sea, Central Arabian Fan

Location: 18°28'N latitude; 66°04'E longitude

Water depth: Echo sounder: 1730 fathoms; 3164 m; set at 1500 m/s
Corrected: 1733 fathoms; 3170 m (Matthews' Tables)

Province and description of the sea floor: Abyssal plain (abyssal deep sea fan) province. The Arabian Fan (or Cone) was formed by very thick accumulations of turbidity current deposits overlying basalt. The sediments are transported through natural, leveed channels from sources in northern India and Pakistan and deposited on the fan.

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity, m/s V_p(3)	Velocity, m/s V_s(4)	Attenuation, k_p(5)	Attenuation, k_s(6)	Density, g/cm^3(7)
Bottom Water				1510.9				1.04227
Sea Floor								
1			Sfc(8)	1495	125	0.05–0.10–0.20	15.0	1.57
			100	1613	349	0.07–0.11–0.19	16.5	1.64
			200	1725	430	0.10–0.12–0.17	18.0	1.77
			300	1833	488	0.12–0.13–0.16	19.5	1.89
			400	1937	554	0.14	21.0	2.01
Sediment and Sedimentary Rock			500	2036	626	0.14	21.0	2.10
	9.86	1975	600	2131	705	0.12	18.0	2.14
			700	2223	775	0.11	16.5	2.18
			800	2310	840	0.10	15.0	2.21
			900	2395	905	0.08	12.0	2.24
			1000	2476	970	0.07	10.5	2.27
			1500	2841	1250	0.04	6.0	2.39
			1975-	3140	1485	0.02	3.0	2.46
2 Basalt			1975+	5400	2744	0.02	0.07	2.72

(U) Notes (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):
   a. First layer:

   $$V_p = 1.495 + 1.20D - 0.253D^2 + 0.034D^3,$$

   where V_p is in km/s and depth in the sea floor (D) is in km.

   b. Lower layers: V_ps from literature.

*Near the end of run S1 the acoustic basement rises into a ridge as indicated on the right-hand side of figure 3. Along track S1 the top of the ridge is at 18°41'N, 66°11'E (water depth is 3080 m). For a geoacoustic model over the ridge, use all information listed under model 3c to a depth of 980 m.

4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).

5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum value, recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).

6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface; proportional to k_p at depth.

7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978, 1976b). Basalt density from Christensen and Salisbury (1975).

8. In the above model, the Sfc values are a composite of the 0- to 3-m depth interval. For a detailed model of this interval, use the detailed model for model 3a and change silt-clay V_ps to 1480 (Sfc, V_p ratio of 0.98) and 1483 at 2.8 m.

(U) In Situ Properties of Bottom Water (U)

True Depth, m	T, °C	S, ppt	P, kg/cm^2	Sound Speed, m/sec	Density, g/cm^3	Impedance, g/cm^2 sec X 10^5
3170	1.80	34.74	328.2	1510.9	1.04227	1.57477

GEOACOUSTIC MODEL 4a (U)

(C) **Geoacoustic model:** 4a　　　　**Area:** Somali Basin, off northeast Africa

Location: 05°08′N latitude; 52°16′E longitude

Water depth: Echo sounder: 2769 fathoms; 5064 m; set at 1500 m/s
Corrected: 2789 fathoms; 5100 m (from station data)

Province and description of the sea floor: Abyssal plain province. The northern Somali Basin, between the east African continental rise and Chain Ridge, is composed of a thick layer of flat-lying turbidite sediments and sedimentary rocks overlying basalt.

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity, m/s V_p(3)	Velocity, m/s V_s(4)	Attenuation, k_p(5)	Attenuation, k_s(6)	Density, g/cm^3(7)
Bottom Water				1543.8				1.05065
Sea Floor								
1			Sfc(8)	1528	125	0.04-0.08-0.18	15.0	1.42
			100	1649	390	0.06-0.09-0.17	19.3	1.68
			200	1760	448	0.09-0.11-0.16	23.5	1.81
			300	1864	507	0.11-0.12-0.15	25.7	1.93
Sediment			400	1960	570	0.14	30.0	2.03
and			500	2048	636	0.14	30.0	2.11
Sedimentary	0.76	1580	600	2128	702	0.12	25.7	2.14
Rock			700	2202	755	0.11	23.5	2.17
			800	2269	810	0.10	21.4	2.19
			900	2330	855	0.08	17.1	2.22
			1000	2385	900	0.07	15.0	2.24
			1500	2582	1050	0.04	8.6	2.30
			1595-	2607	1070	0.03	6.4	2.31
2			1595+	3500	1750	0.03	3.0	2.54
Sedimentary Rock	0.25	940 / 470	2065	3750	1875	0.02	3.0	2.58
			2535-	4000	2000	0.02	3.0	2.61
3								
Basalt			2535+	5300	2680	0.02	0.07	2.70

(U) Notes (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):
   a. First layer:

   $$V_p = 1.528 + 1.25D - 0.45D^2 + 0.0568D^3,$$

   where V_p is in km/s and depth in the sea floor (D) is in km.

   b. Lower layers: V_ps from literature.

4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).

5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum value, recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).

6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface; proportional to k_p at depth.

7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978, 1976b). Basalt density from Christensen and Salisbury (1975).

8. In the above model, the Sfc values are a composite for the 0- to 3-m depth interval. For a detailed model of this interval see the diagram and notes below.

(U) Detail of First 3 Meters (U)

Layer Material	Thickness, s	Thickness, m	Depth, m	Velocity, m/s V_p	Velocity, m/s V_s	Attenuation, k_p	Attenuation, k_s	Density, g/cm^3
Bottom Water				1543.8				1.05065
Sea Floor								
			Sfc	1513	115	0.03-0.07-0.17	15.0	1.39
1a Silt-Clay		2.8						
			2.8-	1517	128	0.03-0 07-0.17	15.0	1.39
			2.8+					
1b Sand-Silt-Clay		0.2		1635	175	0.45-0.06-0.85	13.0	1.78
			3.0-					

(U) Notes

1. The geoacoustic models (such as in the main table) showing thick sediment and sedimentary rock sections over acoustic basement, e.g., basalt, are generalized and do not account for the multiple reflectors usually seen at high frequencies, e.g., in the 3.5-kHz records or in cores.

2. If a detailed, multireflector model is desired, the above sequence of a thicker silt-clay layer and a thinner silt (or other) layer can be alternated to any desired depth. If so, the property values can be corrected for depth as follows:

   a. For the silt-clay layer:

      (1) For V_p: increase V_p using gradients computed from the equation for V_p a function of depth.

      (2) Other properties: vary the value of the property with depth using the appropriate gradient from the values listed in the main table.

b. For the silt (or other layer):

(1) For V_p: increase V_p as above for silt-clay.

(2) For k_p: vary k_p along lines b and c (figure 17).

(3) Other properties: as above for silt-clay.

3. It should be noted that in areas where turbidites form abyssal plains or fans (such as in the Oman Basin, Arabian Fan, and Somali Basin), the reflectors usually represent coarser sediments spilling discontinuously from leveed channels. These reflectors cannot usually be followed over very great distances or correlated from area to area. Any detail, as above, is a gross generalization of widely varying layers (in thickness and properties).

4. The values listed in the main table for Sfc are composite values for the depth interval of 0 to 3 m (illustrated above). Some averaged properties in four cores for this interval, other than those listed above, are as follows (porosity in silt-clay (0 to 100 cm) is salt corrected; porosity in sand-silt-clay based on velocity-porosity relations from other data):

Property	Silt-clay	Sand-silt-clay
Velocity ratio	0.98	1.06
	composite: 0.99	
Porosity, %	79	55
	composite: 77	
Mean grain size, ϕ	8.95	5.48
(number in sample)	(182)	(2)
Grain density, g/cm^3	Average of all samples: 2.66	
(number in sample)		(179)

5. Although these generalized data indicate a sharp top boundary between the silt-clay and sand-silt-clay layers, it is more apt to be gradational in all properties.

(U) In Situ Properties of Bottom Water (U)

True Depth, m	T, °C	S, ppt	P, kg/cm^2	Sound Speed, m/sec	Density, g/cm^3	Impedance, g/cm^2 sec × 10^5
5100	1.38	34.69	529.6	1543.8	1.05065	1.62199

GEOACOUSTIC MODEL 4b (U)

(C) Geoacoustic model: 4b Area: Chain Ridge, Somali Basin Area

Location: 04°44′N latitude; 53°10′E longitude

Water depth: Echo sounder: 2180 fathoms; 3987 m; set at 1500 m/s
Corrected: 2187 fathoms; 4000 m; (from station data)

Province and description of the sea floor: Hill, seamount, ridge province. Chain Ridge runs northeast-southwest and is the eastern boundary of the Somali Basin (as used herein). The ridge is about 2100 m high (2900- to 5000-m depth). This model at middepth represents the west side and top of the ridge.

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity, m/s V_p(3)	Velocity, m/s V_s(4)	Attenuation, k_p(5)	Attenuation, k_s(6)	Density, g/cm^3(7)
Bottom Water				1524.3				1.04594
Sea Floor								
1			Sfc(8)	1540	118	0.05-0.09-0.20	15.0	1.50
Sediment	0.13	217	100	1660	400	0.07-0.10-0.19	16.7	1.69
			200	1772	454	0.10-0.12-0.17	20.0	1.82
			217-	1790	463	0.10-0.12-0.17	20.0	1.84
2								
Basalt			217+	5300	2680	0.02	0.07	2.70

(U) Notes (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):

   a. First layer:

   $$V_p = 1.540 + 1.25D - 0.45D^2 + 0.0568D^3,$$

   where V_p is in km/s and depth in the sea floor (D) is in km.

   b. Lower layers: V_p: from literature.

4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).
5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum value, recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).
6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface; proportional to k_p at depth.
7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978, 1976b). Basalt density from Christensen and Salisbury (1975).

8. No cores were taken at this location. Properties were predicted from files, assuming the sediment was a calcareous (foraminiferal) ooze with a velocity ratio of 1.01, porosity of 72%, and a grain density of 2.67 g/cm^3.

(U) <u>In Situ</u> Properties of Bottom Water (U)

True Depth, m	T, °C	S, ppt	P, kg/cm^2	Sound Speed, m/sec	Density, g/cm^3	Impedance, g/cm^2 sec × 10^5
4000	1.45	34.71	414.6	1524.3	1.04594	1.59433

GEOACOUSTIC MODEL 4c (U)

(C) **Geoacoustic model:** 4c **Area:** Continental Terrace, west of Somali Basin

Location: 05°53'N latitude; 50°36'E longitude

Water depth: Echo sounder: 2180 fathoms; 3987 m; set at 1500 m/s
Corrected: 2187 fathoms; 4000 m (from station data)

Province and description of the sea floor: Continental terrace province. Geoacoustic model 4c is on the lower slopes of the continental rise off East Africa and west of the Somali Basin.

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity, m/s V_p(3)	Velocity, m/s V_s(4)	Attenuation, k_p(5)	Attenuation, k_s(6)	Density, g/cm^3(7)
Bottom Water				1524.3				1.04594
Sea Floor								
1 Sediment and Sedimentary Rock	0.50	970	Sfc(8)	1510	125	0.04-0.07-0.18	15.0	1.42
			100	1631	370	0.06-0.09-0.17	18.8	1.66
			200	1742	438	0.09-0.11-0.16	20.6	1.79
			300	1846	496	0.11-0.12-0.15	24.4	1.91
			400	1942	557	0.14	26.3	2.01
			500	2030	622	0.14	26.3	2.10
			600	2110	687	0.12	22.5	2.13
			700	2184	740	0.11	20.6	2.16
			800	2251	795	0.10	18.8	2.19
			900	2312	840	0.08	15.0	2.21
			970-	2351	870	0.07	13.1	2.22
2 Sedimentary Rock	0.25	940	970+	3500	1750	0.03	3.0	2.54
		470	1400	3750	1875	0.02	3.0	2.58
			1910-	4000	2000	0.02	3.0	2.61
3 Basalt			1910+	5300	2680	0.02	0.07	2.70

(U) **Notes** (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):

   a. First layer:

   $$V_p \approx 1.510 + 1.25D - 0.45D^2 + 0.0568D^3,$$

   where V_p is in km/s and depth in the sea floor (D) is in km.

   b. Lower layers: V_ps from literature.

4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).

5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum value, recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).

6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface; proportional to k_p at depth.

7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978, 1976b). Basalt density from Christensen and Salisbury (1975).

8. In the above model, the Sfc values are a composite for the 0- to 3-m depth interval. For a detailed model of this interval see the diagram and notes below.

(U) Detail of First 3 Meters (U)

Layer Material	Thickness, s	Thickness, m	Depth, m	Velocity, m/s V_p	Velocity, m/s V_s	Attenuation, k_p	Attenuation, k_s	Density, g/cm^3
Bottom Water				1524.3				1.04594
Sea Floor								
			Sfc	1495	115	0.04-0.07-0.18	15.0	1.38
1a Silt-Clay		2.8						
			2.8-	1499	128	0.04-0.07-0.18	15.0	1.38
			2.8+					
1b Sand-Silt-Clay		0.2		1615	175	0.45-0.60-0.85	13.0	1.78
			3.0-					

(U) Notes

1. No cores were taken at this location. It is assumed that the sediment properties are essentially the same here as at the site of model 4a.

2. Notes 1 through 5 for the detailed diagram of geoacoustic model 4a apply.

(U) In Situ Properties of Bottom Water (U)

True Depth, m	T, °C	S, ppt	P, kg/cm^2	Sound Speed m/sec	Density, g/cm^3	Impedance, g/cm^2 sec $\times 10^5$
4000	1.45	34.71	414.6	1524.3	1.04594	1.59433

APPENDIX B. EXTRAPOLATED GEOACOUSTIC MODELS (U)

INTRODUCTION (U)

(U) Part III presented a brief discussion of nine additional geoacoustic models, (labeled "A" for additional) which, with those of Part II (Appendix A), can be used to extrapolate the geophysical and geologic data within geomorphic provinces. The actual models are in this appendix. The locations of these models are indicated in figure 1; exact locations are in the model tables. The geologic setting of the models and the methods used to derive the values listed in the tables are discussed in Parts I and II.

(U) As noted in Appendix A, most of the listed, numerical values for properties in the tables are not rounded off, but are shown as computed (to better indicate trends and gradients and small differences). There is no intent to indicate accuracy or probable errors. All values must be considered as generalizations and estimates, particulary when one model is extrapolated over a general area.

GEOACOUSTIC MODEL A1 (U)

(C) **Geoacoustic model**: A1 **Area**: Arabian Fan, southeast

Location: 09°10'N latitude; 68°13'E longitude

Water depth: Echo sounder: 2477 fathoms; 4530 m; set at 1500 m/s
Corrected: 2493 fathoms, 4559 m (Matthews' Tables)

Province and description of the sea floor: Abyssal plain (abyssal deep sea fan) province. The Arabian Fan (or Cone) was formed by very thick accumulations of turbidity current deposits overlying basalt. The sediments are transported through natural, leveed channels from sources in northern India and Pakistan and deposited on the fan.

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity, m/s V_p(3)	V_s(4)	Attenuation, k_p(5)	k_s(6)	Density, g/cm^3(7)
Bottom Water				1535.6				1.04835
Sea Floor								
1			Sfc(8)	1520	125	0.05-0.09-0.20	15.0	1.54
			100	1638	377	0.07-0.10-0.19	16.7	1.67
Sediment			200	1750	442	0.10-0.12-0.17	20.0	1.80
and	0.35	650	300	1858	503	0.12-0.13-0.16	21.7	1.92
Sedimentary			400	1962	571	0.14	23.3	2.04
Rock			500	2061	646	0.14	23.3	2.11
			600	2156	720	0.12	20.0	[illegible]
			650-	2202	755	0.12	20.0	2.17
2								
Basalt			650+	5400	2744	0.02	0.07	2.72

(U) **Notes** (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):

   a. First layer:

   $$V_p = 1.520 + 1.20D - 0.253D^2 + 0.034D^3,$$

   where V_p is in km/s and depth in the sea floor (D) is in km.

   b. Lower layers: V_ps from literature.

4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).
5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum value recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).
6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface; proportional to k_p at depth.

7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978, 1976b). Basalt density from Christensen and Salisbury (1975).

8. In the above model, the Sfc values are a composite for the 0- to 3-m depth interval. For a detailed model of this interval, use the detailed model for model 3a and change the silt-clay V_ps to 1505 (Sfc, V_p ratio of 0.98) and 1508 at 2.8 m; use density of 1.52 g/cm^3.

GEOACOUSTIC MODEL A2 (U)

(C) **Geoacoustic model**: A2 **Area**: Arabian Fan, south central

Location: 13°17′N latitude; 63°38′E longitude

Water depth: Echo sounder: 2248 fathoms; 4112 m; set at 1500 m/s
Corrected: 2259 fathoms; 4132 m (Matthews' Tables)

Province and description of the sea floor: Abyssal plain (abyssal deep sea fan) province. The Arabian Fan (or Cone) was formed by very thick accumulations of turbidity current deposits overlying basalt. The sediments are transported through natural, leveed channels from sources in northern India and Pakistan and deposited on the fan.

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity, m/s V_p(3)	Velocity, m/s V_s(4)	Attenuation, k_p(5)	Attenuation, k_s(6)	Density, g/cm^3(7)
Bottom Water				1527.9				1.04651
Sea Floor								
1			Sfc(8)	1513	125	0.05-0.10-0.20	15.0	1.57
			100	1631	369	0.07-0.11-0.19	16.5	1.66
			200	1743	439	0.10-0.12-0.17	18.0	1.79
			300	1851	499	0.12-0.13-0.16	19.5	1.91
			400	1955	566	0.14	21.0	2.03
Sediment			500	2054	641	0.14	21.0	2.11
and			600	2149	720	0.12	18.0	2.15
Sedimentary	1.0	2440	700	2241	786	0.11	16.5	2.18
Rock			800	2328	854	0.10	15.0	2.22
			900	2413	920	0.08	12.0	2.25
			1000	2494	983	0.07	10.5	2.27
			1500	2859	1268	0.04	6.0	2.39
			2000	3173	1513	0.02	3.0	2.47
			2440-	3420	1710	0.02	3.0	2.53
2 Basalt			2440+	5400	2744	0.02	0.07	2.72

(U) **Notes** (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):
   a. First layer:
   $$V_p = 1.513 + 1.20D - 0.253D^2 + 0.034D^3,$$
   where V_p is in km/s and depth in the sea floor (D) is in km.
   b. Lower layers: V_ps from literature.
4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).

5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum value, recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).

6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface; proportional to k_p at depth.

7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978, 1976b). Basalt density from Christensen and Salisbury (1975).

8. In the above model, the Sfc values are a composite for the 0- to 3-m depth interval. For a detailed model of this interval, use the detailed model for model 3a and change silt-clay V_ps to 1487 (Sfc, V_p ratio of 0.98) and 1500 at 2.8 m.

GEOACOUSTIC MODEL A3a (U)

(C) **Geoacoustic model:** A3a **Area:** Southern Arabian Fan

Location: 10°00'N latitude; 61°58'E longitude

Water depth: Echo sounder: 2443 fathoms; 4467 m; set at 1500 m/s
Corrected: 2458 fathoms; 4495 m (Matthews' Tables)

Province and description of the sea floor: Abyssal plain (abyssal deep sea fan) province. The Arabian Fan (or Cone) was formed by very thick accumulations of turbidity current deposits overlying basalt. The sediments are transported through natural, leveed channels from sources in northern India and Pakistan and deposited on the fan.

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity, m/s V_p(3)	Velocity, m/s V_s(4)	Attenuation, k_p(5)	Attenuation, k_s(6)	Density, g/cm^3(7)
Bottom Water				1534.4				1.04808
Sea Floor								
1			Sfc(8)	1519	125	0.05-0.10-0.20	15.0	1.55
			100	1637	376	0.07-0.11-0.19	16.5	1.67
			200	1749	442	0.10-0.12-0.17	18.0	1.80
			300	1857	502	0.12-0.13-0.16	19.5	1.92
Sediment and Sedimentary Rock			400	1961	571	0.14	21.0	2.04
	0.50	990	500	2060	645	0.14	21.0	2.11
			600	2155	720	0.12	18.0	2.15
			700	2247	790	0.11	16.5	2.18
			800	2334	860	0.10	15.0	2.22
			900	2419	925	0.08	12.0	2.25
			900-	2492	982	0.07	10.5	2.27
2								
Basalt			900+	5400	2744	0.02	0.07	2.72

(U) **Notes** (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):

   a. First layer:

   $$V_p = 1.519 + 1.20D - 0.253D^2 + 0.034D^3$$

   where V_p is in km/s and depth in the sea floor (D) is in km.

   b. Lower layers. V_ps from literature.
4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).
5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum value, recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).

6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface, proportional to k_p at depth.

7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978 1976b). Basalt density from Christensen and Salisbury (1975).

8. In the above model, the Sfc values are a composite for the 0- to 3-m depth interval. For a detailed model of this interval, use the detailed model or model 3a and change the silt-clay V_ps to 1504 (Sfc, V_p ratio of 0.98) and 1507 at 2.8 m; change density at Sfc to 1.53 g/cm^3.

GEOACOUSTIC MODEL A3b (U)

(C) **Geoacoustic model:** A3b* **Area:** Arabian Fan, southwest

Location: 12°00'N latitude; 60°10'E longitude

Water depth: Echo sounder: 2392 fathoms; 4375 m; set at 1500 m/s
Corrected. 2406 fathoms; 4400 m (Matthews' Tables)

Province and description of the sea floor: Abyssal plain (abyssal deep sea fan) province. The Arabian Fan (or Cone) was formed by very thick accumulations of turbidity current deposits overlying basalt. The sediments are transported through natural, leveed channels from sources in northern India and Pakistan and deposited on the fan.

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity, m/s V_p(3)	Velocity, m/s V_s(4)	Attenuation, k_p(5)	Attenuation, k_s(6)	Density, g/cm^3(7)
Bottom Water				1532.7				1.04767
Sea Floor								
1 Sediment and Sedimentary Rock		1000	Sfc(8)	1517	125	0.05-0.10-0.20	15.0	1.55
				(100 to 900 m: same as for geoacoustic model A3a)				
			1000-	2500	990	0.07	10.5	2.28
2 Basalt			1000+	5400	2744	0.02	0.07	2.72

(U) **Notes** (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):
   a. First layer

   $$V_p = 1.519 + 1.20D - 0.253D^2 + 0.034D^3,$$

   where V_p is in km/s and depth in the sea floor (D) is in km.

   b. Lower layers: V_ps from literature.
4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).
5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum value, recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).

*This model was set on the 1000-m-sediment-thickness contour of Naini and Talwani (personal communication, 1977).

6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface; proportional to k_p at depth.

7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978, 1976b). Basalt density from Christensen and Salisbury (1975).

8. In the above model, the Sfc values are a composite for the 0- to 3-m depth interval. For a detailed model of this interval, use the detailed model or model 3a and change the silt-clay V_ps to 1504 (Sfc, V_p ratio of 0.98) and 1507 at 2.8 m; change density at Sfc to 1.53 g/cm^3.

GEOACOUSTIC MODEL A3c (U)

(C) **Geoacoustic model:** A3c* **Area:** Arabian Fan, southeast

Location: 11°45'N latitude; 68°00'E longitude

Water depth: Echo sounder: 2373 fathoms, 4340 m; set at 1500 m/s
Corrected: 2387 fathoms; 4365 m (Matthews' Tables)

Province and description of the sea floor: Abyssal plain (abyssal deep sea fan) province. The Arabian Fan (or Cone) was formed by very thick accumulations of turbidity current deposits overlying basalt. The sediments are transported through natural, leveed channels from sources in northern India and Pakistan and deposited on the fan.

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity, m/s $V_p(3)$	Velocity, m/s $V_s(4)$	Attenuation, $k_p(5)$	Attenuation, $k_s(6)$	Density, $g/cm^3(7)$
Bottom Water				1532.1				1.04752
Sea Floor								
1 Sediment and Sedimentary Rock		1000	Sfc(8)	1517	125	0.05-0.10-0.20	15.0	1.55
			(100 to 900 m: same as for geoacoustic model A3a)					
			1000-	2500	990	0.07	10.5	2.28
2 Basalt			1000+	5400	2744	0.02	0.07	2.72

(U) **Notes** (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):
   a. First layer.

   $$V_p = 1.519 + 1.20D - 0.253D^2 + 0.034D^3,$$

   where V_p is in km/s and depth in the sea floor (D) is in km.

   b. Lower layers: V_ps from literature.
4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).
5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum value, recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).

*This model was set on the 1000-m-sediment-thickness contour of Naini and Talwani (personal communication, 1977)

6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface; proportional to k_p at depth.

7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978, 1976b). Basalt density from Christensen and Salisbury (1975).

8. In the above model, the Sfc values are a composite for the 0- to 3-m depth interval. For a detailed model of this interval, use the detailed model or model 3a and change the silt-clay V_ps to 1504 (Sfc, V_p ratio of 0.98) and 1507 at 2.8 m; change density at Sfc to 1.53 g/cm^3.

GEOACOUSTIC MODEL A4a (U)

(C) **Geoacoustic model**: A4a* **Area**: Arabian Fan, south end

Location: 08°20′N latitude; 65°00′E longitude

Water depth: Echo sounder 2504 fathoms; 4580 m; set at 1500 m/s
Corrected: 2521 fathoms; 4610 m (Matthews' Tables)

Province and description of the sea floor: Abyssal plain (abyssal deep sea fan) province. The Arabian Fan (or Cone) was formed by very thick accumulations of turbidity current deposits overlying basalt. The sediments are transported through natural, leveed channels from sources in northern India and Pakistan and deposited on the fan.

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity, m/s $V_p(3)$	Velocity, m/s $V_s(4)$	Attenuation, $k_p(5)$	Attenuation, $k_s(6)$	Density, $g/cm^3(7)$
Bottom Water				1536.5				1.04857
Sea Floor								
1 Sediment		500	Sfc(8)	1520	125	0.05-0.10-0.20	15.0	1.55
			100	1637	376	0.07-0.11-0.19	16.5	1.67
			200	1749	442	0.10-0.12-0.17	18.0	1.80
			300	1847	502	0.12-0.13-0.16	19.5	1.92
			400	1961	571	0.14	21.0	2.04
			500-	2060	645	0.14	21.0	2.11
2 Basalt			500+	5400	2744	0.02	0.07	2.72

(U) **Notes** (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):
   a. First layer:

   $$V_p = 1.520 + 1.20D - 0.253D^2 + 0.034D^3,$$

   where V_p is in km/s and depth in the sea floor (D) is in km.

   b. Lower layers: V_ps from literature.
4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).
5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum value, recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).
6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface; proportional to k_p at depth.

*This model was set on the 500-m-sediment-thickness contour of Naini and Talwani (personal communication, 1977).

7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978, 1976b). Basalt density from Christensen and Salisbury (1975).

8. In the above model, the Sfc values are a composite for the 0- to 3-m depth interval. For a detailed model of this interval, use the detailed model or model 3a and change the silt-clay V_ps to 1505 (Sfc, V_p ratio of 0.98) and 1508 at 2.8 m; change density at Sfc to 1.53 g/cm^3.

GEOACOUSTIC MODEL A4b (U)

(C) Geoacoustic model: A4b*   Area: Arabian Fan, south end

Location: 09°00′N latitude; 61°30′E longitude

Water depth: Echo sounder: 2461 fathoms; 4500 m; set at 1500 m/s
Corrected: 2476 fathoms; 4529 m (Matthews' Tables)

Province and description of the sea floor: Abyssal plain (abyssal deep sea fan) province. The Arabian Fan (or Cone) was formed by very thick accumulations of turbidity current deposits overlying basalt. The sediments are transported through natural, leveed channels from sources in northern India and Pakistan and deposited on the fan.

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity, m/s V_p(3)	Velocity, m/s V_s(4)	Attenuation, k_p(5)	Attenuation, k_s(6)	Density, g/cm^3(7)
Bottom Water				1535.0				1.04822
Sea Floor								
1			Sfc(8)	1520	125	0.05-0.10-0.20	15.0	1.55
			100	1637	376	0.07-0.11-0.19	16.5	1.67
			200	1749	442	0.10-0.12-0.17	18.0	1.80
Sediment		500	300	1847	502	0.12-0.13-0.16	19.5	1.92
			400	1961	571	0.14	21.0	2.04
			500-	2060	645	0.14	21.0	2.11
2								
Basalt			500+	5400	2744	0.02	0.07	2.72

(U) Notes (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):

   a. First layer:

   $$V_p = 1.520 + 1.20D - 0.253D^2 + 0.034D^3,$$

   where V_p is in km/s and depth in the sea floor (D) is in km.

   b. Lower layers: V_ps from literature.

*This model was set on the 500-m-sediment-thickness contour of Naini and Talwani (personal communication, 1977).

4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).

5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three listed values to 300 m are probable minimum value, recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).

6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz. Based on Hamilton (1976c) at surface; proportional to k_p at depth.

7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978, 1976b). Basalt density from Christensen and Salisbury (1975).

8. In the above model, the Sfc values are a composite for the 0- to 3-m depth interval. For a detailed model of this interval, use the detailed model or model 3a and change the silt-clay V_ps to 1505 (Sfc, V_p ratio of 0.98) and 1508 at 2.8 m; change density at Sfc to 1.53 g/cm^3.

GEOACOUSTIC MODEL A5 (U)

(C) **Geoacoustic model:** A5 **Area:** Arabian Fan, northwest

Location: 20°00'N latitude; 63°10'E longitude

Water depth: Echo sounder: 1859 fathoms; 3400 m; set at 1500 m/s
Corrected: 1864 fathoms; 3409 m (Matthews' Tables)

Province and description of the sea floor: Abyssal plain (abyssal deep sea fan) province. The Arabian Fan (or Cone) was formed by very thick accumulations of turbidity current deposits overlying basalt. The sediments are transported through natural, leveed channels from sources in northern India and Pakistan and deposited on the fan

Layer Material	Thickness, s(1)	Thickness, m(2)	Depth, m	Velocity, m/s $V_p(3)$	Velocity, m/s $V_s(4)$	Attenuation, $k_p(5)$	Attenuation, $k_s(6)$	Density, $g/cm^3(7)$
Bottom Water				1515.0				1.04333
Sea Floor								
1 Sediment and Sedimentary Rock		2300	Sfc(8)	1500	125	0.10	15.0	1.57
			(100 to 2000 m: same as for geoacoustic model 3b)					
			2300-	3335	1640	0.02	3.0	2.51
2 Basalt			2300+	5400	2744	0.02	0.07	2.72

(U) **Notes** (for further derivation of values and discussions see Part II, "Methods and Results")

1. Thickness, s (in seconds of one-way sound travel time) from reflection records.
2. Thickness, m, from one-way travel time and layer mean velocity.
3. V_p (compressional wave (sound) velocity):

   a. First layer:

   $$V_p = 1.501 + 1.20D - 0.253D^2 + 0.034D^3,$$

   where V_p is in km/s and depth in the sea floor (D) is in km.

   b. Lower layers: V_ps from literature.
4. V_s (shear wave velocity): From unpublished study by Hamilton of V_p/V_s ratios in marine sediments and rocks. Basalt V_s from Christensen and Salisbury (1975).
5. k_p (constant in attenuation of compressional waves (α_p) in dB/m = $k_p f$, where f is frequency in kHz). The three values to 300 m are probable minimum value, recommended value for first trial in bottom-loss modeling, and probable maximum value. From Hamilton (1972, 1974, 1976a).

*Sediment thickness from Naini and Talwani (personal communication, 1977).

6. k_s (constant in attenuation of shear waves (α_s) in dB/m = $k_s f$, where f is frequency in kHz). Based on Hamilton (1976c) at surface; proportional to k_p at depth.

7. Density (saturated bulk density in situ). Surface density computed from core data. Density at depth from Hamilton (1978, 1976b). Basalt density from Christensen and Salisbury (1975).

8. In the above model, the Sfc values are a composite for the 0- to 3-m depth interval. If a detailed model of this interval is desired, use the detailed model in 3a and change silt-clay V_ps to 1486 (Sfc, V_p ratio of 0.98) and 1489 at 2.8 m.

GEOACOUSTIC MODEL A6 (U)

(C) **Geoacoustic model**: A6 **Area**: Carlsberg Ridge

Location: Tops of peaks and ridges on Carlsberg Ridge

Water depth: Variable; most peaks and ridges have top depths between 1500 and 2000 m.

Province and description of the sea floor: See notes below.

Layer Material	Thickness, s	Thickness, m	Depth, m	Velocity, m/s V_p	Velocity, m/s V_s	Attenuation, k_p	Attenuation, k_s	Density, g/cm^3
Bottom Water				(Variable, according to depth)				
Sea Floor								
1 Basalt			Sfc	5300	2680	0.03	0.07	2.70

(U) **Notes**

- On and near the tops of the peaks and ridges of the Carlsberg Ridge there is little or no sediment accumulation, apart from thin layers of calcareous material in hollows and between rocks. The sea floor is apt to be composed of congealed lava flows and lava blocks. Steep escarpments and fissures are common. The information above indicates a model in which basaltic lavas are exposed at the sea floor with no sediment cover.

- The compressional wave velocity of 5300 m/s was measured by the Soviets along a refraction line passing through 5°00′N latitude, 62°30′E longitude. Other data are from Christensen and Salisbury (1975) and from literature data in Hamilton's files.

APPENDIX C. OUTLINE OF STEPS TO DERIVE A GEOACOUSTIC MODEL (U)

INTRODUCTION (U)

(U) This appendix is an outline of "Methods and Results" in Part II. It summarizes the procedures used to derive the geoacoustic models of the sea floor in this report.

WATER MASS INFORMATION (U)

1. (U) Expedition SV/STD casts furnished temperature, salinity, and sound speed as functions of true water depth. Data from these casts were averaged in areas of interest (as were the data indicated below).

2. (U) From the cast data, computations were made of true depth as a function of echo-sounder depth and consequent corrections and true depth as a function of pressure and density.

3. (U) The true depth at the site of the model was determined from the corrected, expedition echo-sounder depth.

4. (U) The bottom-water temperature, salinity, sound speed, pressure, and density were extrapolated to the true depth of the sea floor. These values, plus computed impedance, were placed in a table which became part of the geoacoustical model.

BATHYMETRIC CHARTS, SHIPS' TRACKS, AND PROFILES OF THE SEA FLOOR (U)

1. (U) The best available bathymetric charts of the area (at plotting sheet size) were obtained from NAVOCEANO (via NORDA).

2. (U) The smoothed track of the expedition's ships (KINGSPORT, WILKES, in part MIZAR) were plotted on the bathymetric chart with date-time notations along the track.

3. (U) Soundings from echo-sounder records were plotted along the ships' tracks.

4. (U) The original depth contours of the sea floor on the bathymetric charts were changed to conform with the soundings along the ships' tracks. The resulting set of charts (five in this case) thus showed the expedition's ship movements on a "best available" bathymetric chart. The final smoothed, drafted chart showed only the KINGSPORT track; data to plot other tracks can be obtained from NORDA (Code 341).

5. (U) Computer-drawn profiles of the sea floor were constructed from the ship-track and echo-sounder data (largely forwarded from NORDA).

6. (U) The five large bathymetric charts were photographically reduced, pasted together, and further reduced to form a large-scale chart of the entire area (figure 1 is a further reduction to page size).

PROPERTIES OF THE SEA FLOOR (LISTED IN THE MAIN TABLE AND FOOTNOTES) (U)

Compressional Wave (Sound) Velocity (U)

1. (U) The value of sound velocity at the sediment surface (V_o) was determined from measurements in cored sediments by NAVOCEANO. These measurements were collected and averaged for a general area of interest, and a composite of the upper 1 or 3 m was used with the 3.5-kHz records to form a generalized surface layer in the area. The velocity measurements were corrected to in situ conditions following Hamilton (1971). This value was listed for Sfc in the main table for each model.

2. (U) Sound velocity as a function of depth in the sea floor was determined in the various areas from sonobuoy measurements of layer interval velocities. Regression equations were computed for instantaneous velocity and mean velocity as a function of one-way sound travel time in the sea floor. From these data, equations were computed for instantaneous velocity as a function of depth in the sea floor. All curves and equations were forced through the in situ value of velocity at the sediment surface (figures 11 and 12 and equations 1 through 9). Data analyses followed LePichon et al. (1968), Houtz et al. (1968, 1970), Houtz (1974), and Hamilton et al. (1974, 1977).

3. (U) After first layer thicknesses were established (as below), values of sound velocity were computed for each 100-m to 1000-m depth and for each 500-m depth thereafter by using the equations for velocity as a function of depth (3, 6, and 9). These values are listed under V_p in the main table for each geoacoustic model.

4. (U) Basalt velocities were estimated from refraction surveys in the general area (published in the literature).

5. (U) The values of compressional wave velocity gradients can be computed between any two depths by using the equations for velocity as a function of depth.

Sediment and Rock Layer Thicknesses (U)

1. (U) Two-way sound travel times (reflection times) through the sediment and rock layers of the sea floor were measured directly from acoustic reflection records taken during the expedition, e.g., figures 2 through 6. These travel times were divided by two to obtain one-way travel times; these are listed under "Thickness, s" in the main tables.

2. (U) The one-way travel times for the first sediment and sedimentary rock layer were then used with the equations for mean velocity as a function of one-way travel time (equations 2, 5, and 8) to determine mean velocity ($\bar{V}_p$) for the given travel time (t). The thickness (h) of a layer was then computed ($h = \bar{V}_p t$). These thicknesses are listed under "Thickness, m" in the main tables.

3. (U) For some lower sedimentary rock layers (areas 1 and 4), seismic refraction measurements from the literature established velocities at the top of the layer (the equivalent of V_o at the sediment surface). Linear velocity gradients (a) in these layers were estimated from Naini and Talwani (1977). Layer thicknesses were computed using the equation: $h = V_o\,(e^{at} - 1)/a$, where the one-way travel time (t) was measured from acoustic reflection records (see above). These data also established the layer mean velocity (at the

midpoint of the layer) and the velocity at the bottom of the layer. This method was also used for some very thin sediment layers where the sediment surface velocity (V_0) was known from cores or was predicted, and velocity gradients were estimated from equation (10).

Shear Wave Velocity (U)

1. (U) In the models, the velocity of shear waves in the first layer of sediments and sedimentary rocks was determined from the relationship between shear and compressional waves (unpublished study). The basic information on shear wave velocity as a function of depth in silt-clays came from Hamilton (1976d). Averaged data from 17 areas of mostly turbidites were used to define compressional wave velocity as a function of depth (unpublished study). When these two data sets were linked at common depths, regression equations could be determined to link compressional and shear wave velocities to depths of about 700 m. The resulting curves of compressional velocity as a function shear velocity are shown in figure 13. The linear curve between compressional velocities of about 2.15 and 3.4 km/s was extrapolated on very little selected data. These same equations were used for calcareous ooze and pelagic clay because of lack of sufficient data for these sediment types.

2. (U) The equations of Christensen and Salisbury (1975) from measurements in basalts drilled by the Deep Sea Drilling Project were used to predict shear wave velocities in basalt (figure 14).

3. (U) When the rock was considered to be limestone, a V_p/V_s ratio of 1.90 (unpublished study) was used with the literature value for compressional velocity to predict the shear wave velocity.

Compressional Wave Attenuation (U)

1. (U) Predicted sound attenuation in the sediment surface was based on interrelationships between attenuation and sediment porosity and mean grain size (Hamilton, 1972, 1974, 1976a). Figures 15 and 16 are reproduced from these reports. In the reports cited, attenuation of compressional waves (α_p) in decibels per meter is related to the first power of frequency (f) in kilohertz by the constant (k_p) in the equation $\alpha_p = k_p f$. The three values of κ_p listed in the main table for each model are minimum value, recommended value for first trial by acousticians in reconciling experiments with theory, and the maximum value. The values can be inserted into the equation and used at any frequency.

2. (U) The scatter in the data requires that predictions include probable maximum and probable minimum values of k_p (indicated by the dashed lines in figures 15 and 16). For higher porosity silt-clays the lower range of values for k_p is approximately 0.03 or 0.05; the maximum values are about 0.2. Recent measurements in situ by Tyce (unpublished) indicate most values of k_p in higher porosity sediments may fall between 0.03 and 0.10.

3. (U) Values of k_p as a function of depth in the sediments, sedimentary rocks, and basalt were estimated from the report by Hamilton (1976a). Figure 17 is reproduced from that report.

Shear Wave Attenuation (U)

1. (U) The very sparse data on attenuation of shear waves in marine sediments and rocks were recently reviewed (Hamilton, 1976c). In this report, attenuation of shear waves (α_s) in decibels per meter was related to the first power of frequency (f) through the constant (k_s) in the equation:

$$\alpha_s = k_s f \quad .$$

2. (U) The values of k_s at the sediment surface or in lower rock layers of the geo-acoustic models were selected from the data in Hamilton (1976c). These values were silt-clays, 15; sand-silt, 13; mudstone, 10; shale, 3; and basalt, 0.07 (from Levykin, 1965).

3. (U) In the absence of data on variations of attenuation of shear waves with depth, it was assumed for this report that shear wave attenuation varied with depth in the sea floor proportionally to compressional wave attenuation. Experiments in the laboratory indicate that this is approximately true in sands and low-porosity igneous rocks.

Density (U)

1. (U) The saturated bulk density of the sediment surface (ρ_{sat}) was computed from the averaged coring data (generalized for each area) by using the fractional porosity (n), the density of bottom water (ρ_w), and the bulk density of mineral grains (ρ_s) in the equation

$$\rho_{sat} = n\rho_w + (1 - n)\,\rho_s \quad .$$

2. (U) Density at depth in some soft, thin sediment layers was based on Hamilton (1976b).

3. (U) In the thick sediment and sedimentary rock layers (most of the models), density as a function of depth was determined by the relationship between compressional wave velocity and density as summarized by Hamilton (1978). Figure 18 for silt-clay, turbidites, mudstone, and shale and figure 14 for basalts (Christensen and Salisbury, 1975) are reproduced from the 1978 report. The curves and equations allow reasonable estimates of densities in common sediments and sedimentary rocks and basalts, given values of compressional wave velocities from reflection and refraction surveys.

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NORDATN44	Bucca, P. J.	ENVIRONMENTAL VARIABILITY DURING THE CHURCH STROKE II CRUISE FIVE EXERCISE (U)	Naval Ocean R&D Activity	790201	ADC020353; NS; AU; ND	C
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USIControl674779	Williams, W., et al.	REPORT OF THE LRAPP EXERCISE PLANNING WORKSHOP TRACOR INC ROCKVILLE MD 16 - 17 OCTOBER 1978 (U)	Underwater Systems, Inc.	790302	NS; ND	C
NOSCTR357	Hamilton, E. L., et al.	GEOACOUSTIC MODELS OF THE SEAFLOOR: GULF OF OMAN, ARABIAN SEA, AND SOMALI BASIN (U)	Naval Ocean Systems Center	790615	ND	C
Unavailable	Unavailable	RAPIDLY DEPLOYABLE SURVEILLANCE SYST (RDSS) ACOUSTIC VALIDATION TEST (AVT) EXERCISE PLAN (U)	Naval Electronic Systems Command	790625	AU	C
LRAPPRC79027	Brunson, B. A., et al.	GULF OF MEXICO AND CARIBBEAN SEA DATA AND MODEL BASE REPORT (U)	Tracor, Inc.	790701	ADC019153; NS; ND	C
Unavailable	Unavailable	BEARING STAKE BMS DATA QUALITY ASSESSMENT REPORT (U)	University of Texas, Applied Research Laboratories	790705	AU	C
PME12430	Unavailable	RAPIDLY DEPLOYABLE SURVEILLANCE SYSTEM (RDSS) ACOUSTIC VALIDATION TEST (AVT) DATA REDUCTION AND ANALYSIS PLAN (U)	Naval Electronic Systems Command	790815	NS; AU	C
Unavailable	Unavailable	RAPIDLY DEPLOYABLE SURVEILLANCE SYSTEM (RDSS) ACOUSTIC VALIDATION TEST (AVT) EXERCISE PLAN (U)	Naval Electronic Systems Command	790917	AU	C
NOSCTR467	Pedersen, M. A., et al.	PROPAGATION LOSS ASSESSMENT OF THE BEARING STAKE EXERCISE (U)	Naval Ocean Systems Center	790928	ADC020845; NS; AU; ND	C
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